Micro/NanoMachined and Optical Compressor Photodetector R&D

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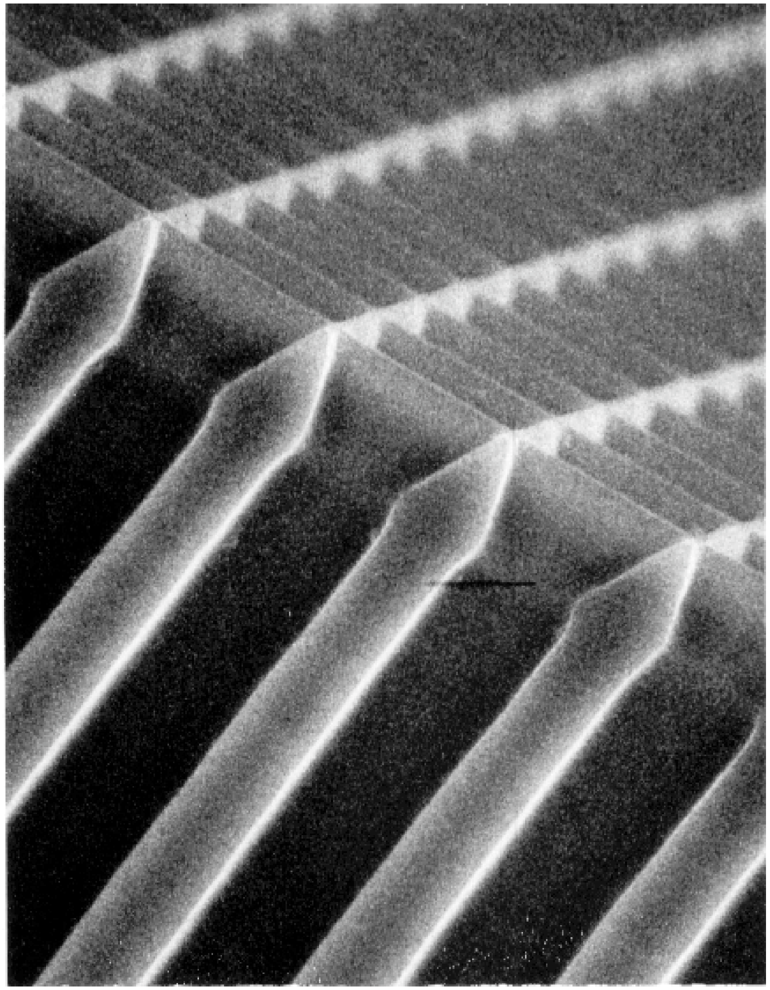
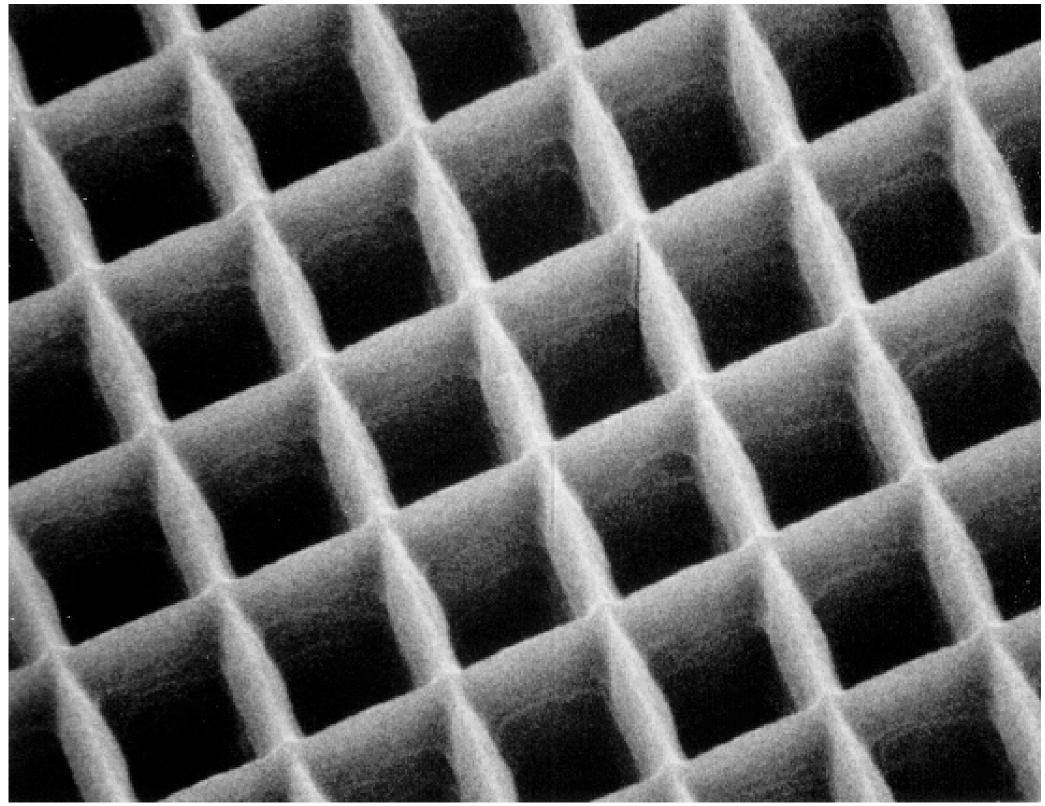
Silicon Micromachining - I

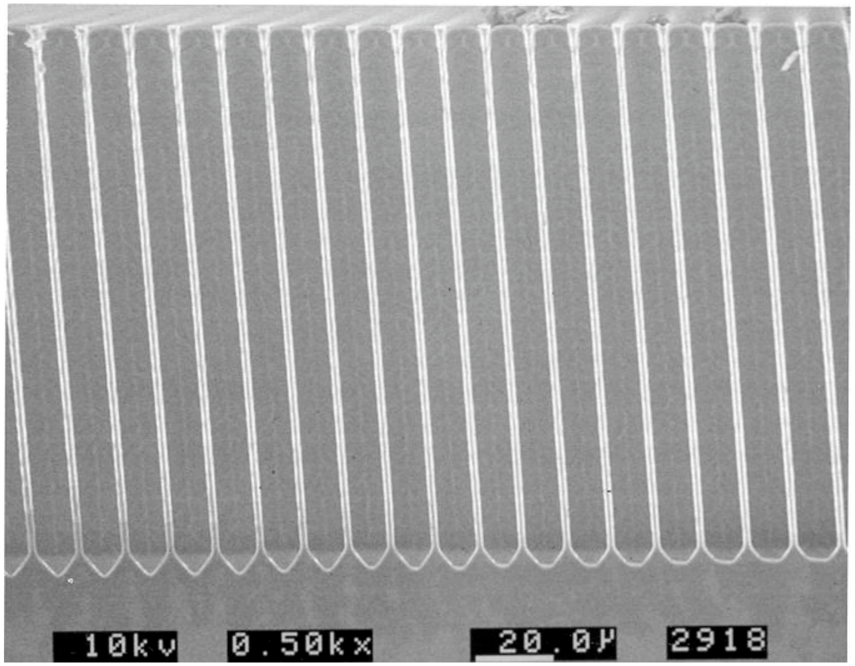


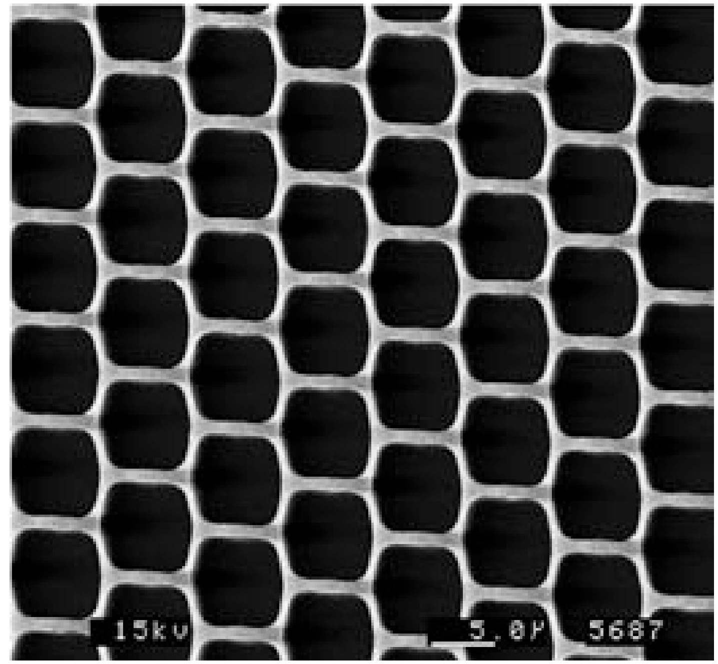


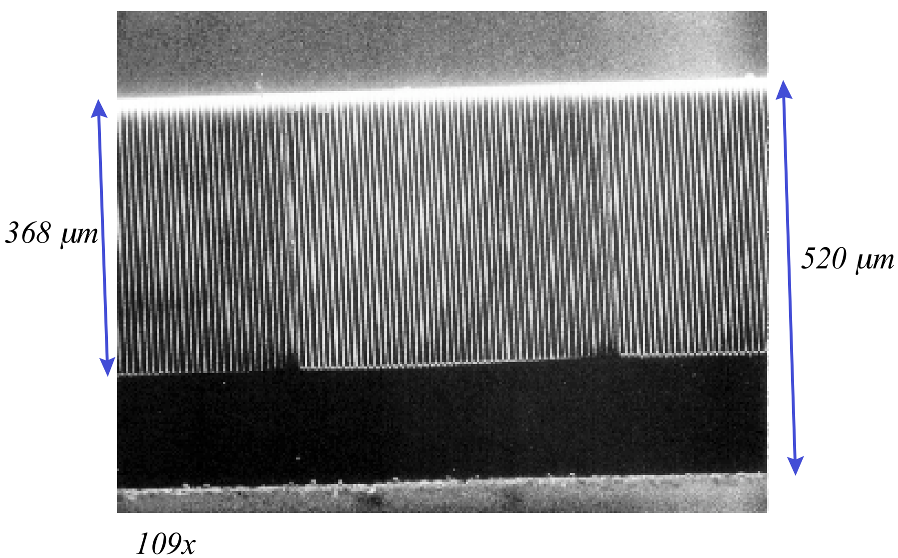
6 μm channels on 8 μm centers

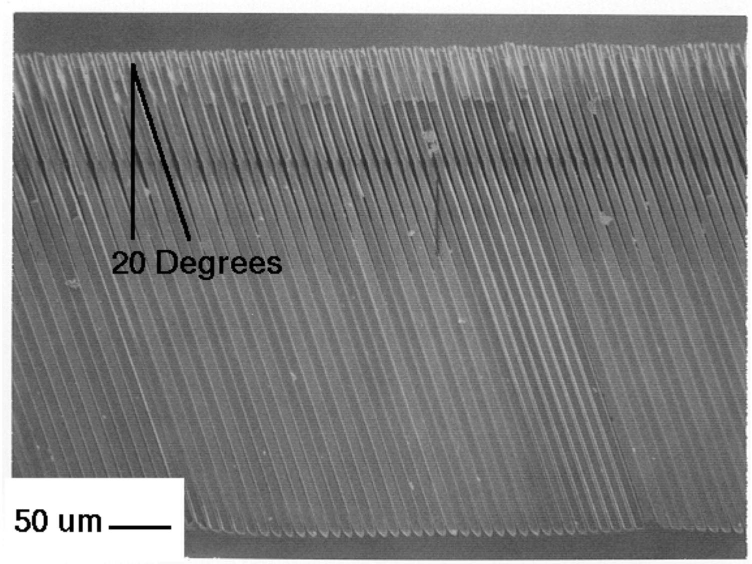
(note tapered throat, precision placement)

High Aspect Si Micro/NanoMachining

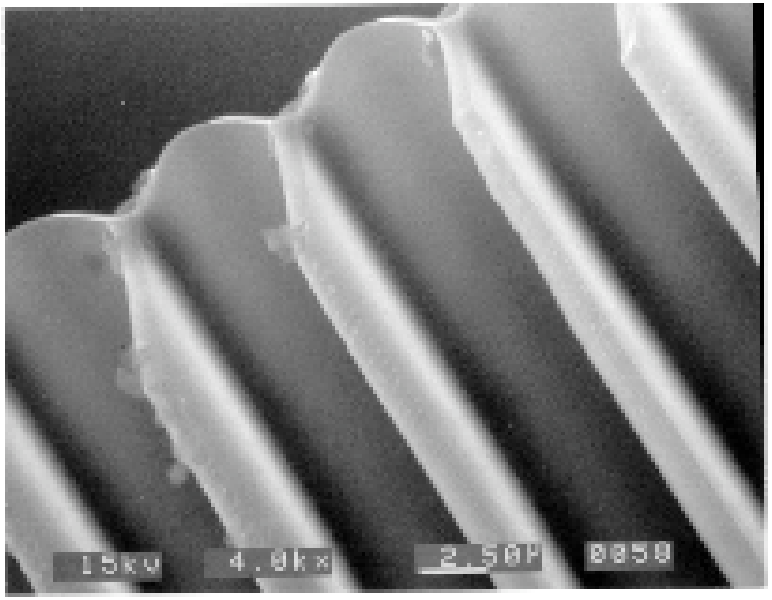


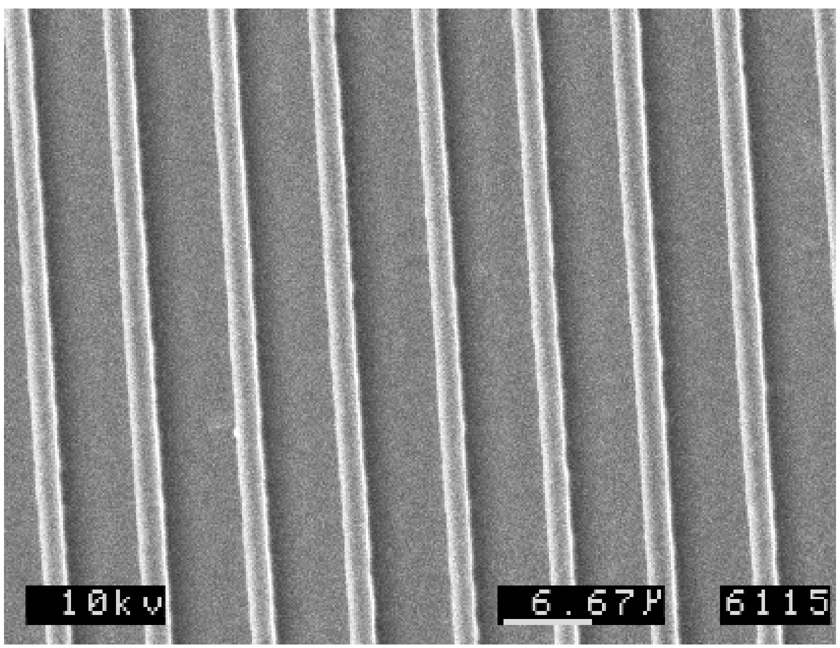






Si nanomachining





<100nm walls

- >90% Si removed
- Holes ~ 30 nm
- Aspect ratio > 300:1

Smooth high aspect walls

Jiffy Si Micro/NanoMachining

"Photoelectrochemical etch"

A hole migrates to the surface and recombines with a cation at the Si-liquid boundary, leaving the Si.

Control by:

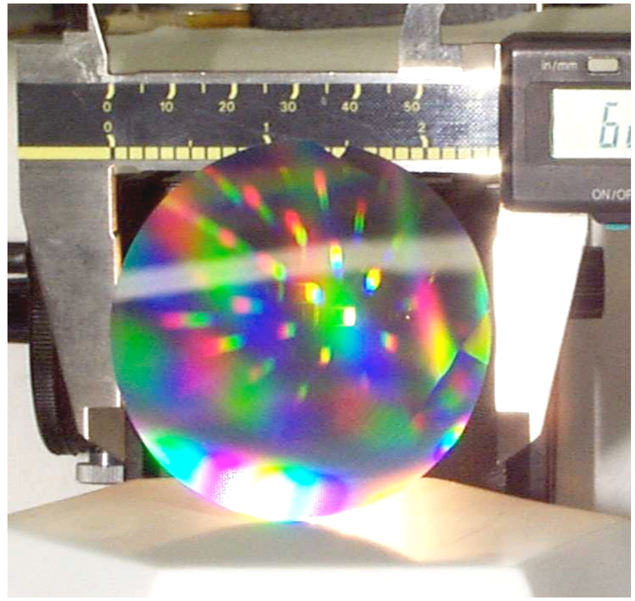
- Electric field directions - Pattern electrodes important (F/B)
- Carrier generation by light - Pattern light
- Voltage/time profile
- Current Density and Time Profiles
- Solution Temperature
- Composition/Concentration
- Back-reactants/Back-reactions (rate equations)
- Flow rates
- Crystal orientations, *dopants/levels (n,p types)*

Micro/Nano/Machining Features

- Photolithographically Precise - leverages VLSI tech
- 10's nm < Features Sizes < mm + >90% open
- 1:1 < aspect ratio < 300:1
- Low Cost (good throughput)
- Large Areas ~ wafer size
- Technology for many semiconductors (GaAs, diamond+LN_2)

Uses: 3-D electronics/thru-wafer vias, Isolation/low K (Si on air,…), ElectroMicrofluidics, scintillator plates, filters, robust lightweight materials, ….

Si Microchannel Plates



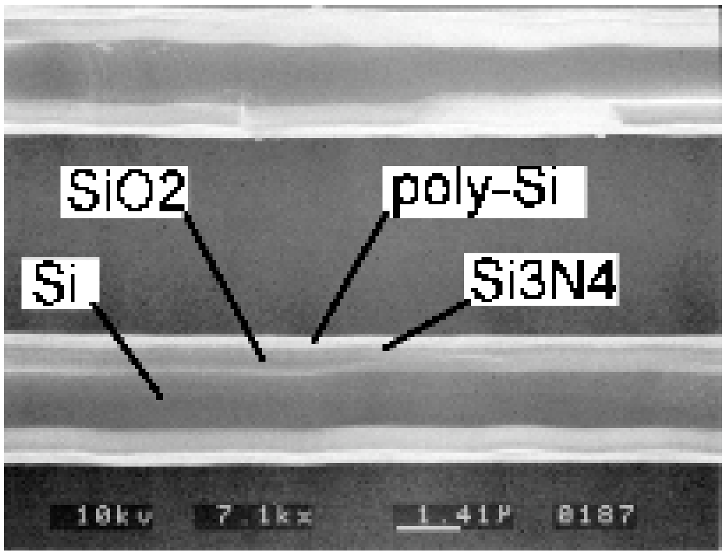
Porous Si: velvety black coated plate square diffraction

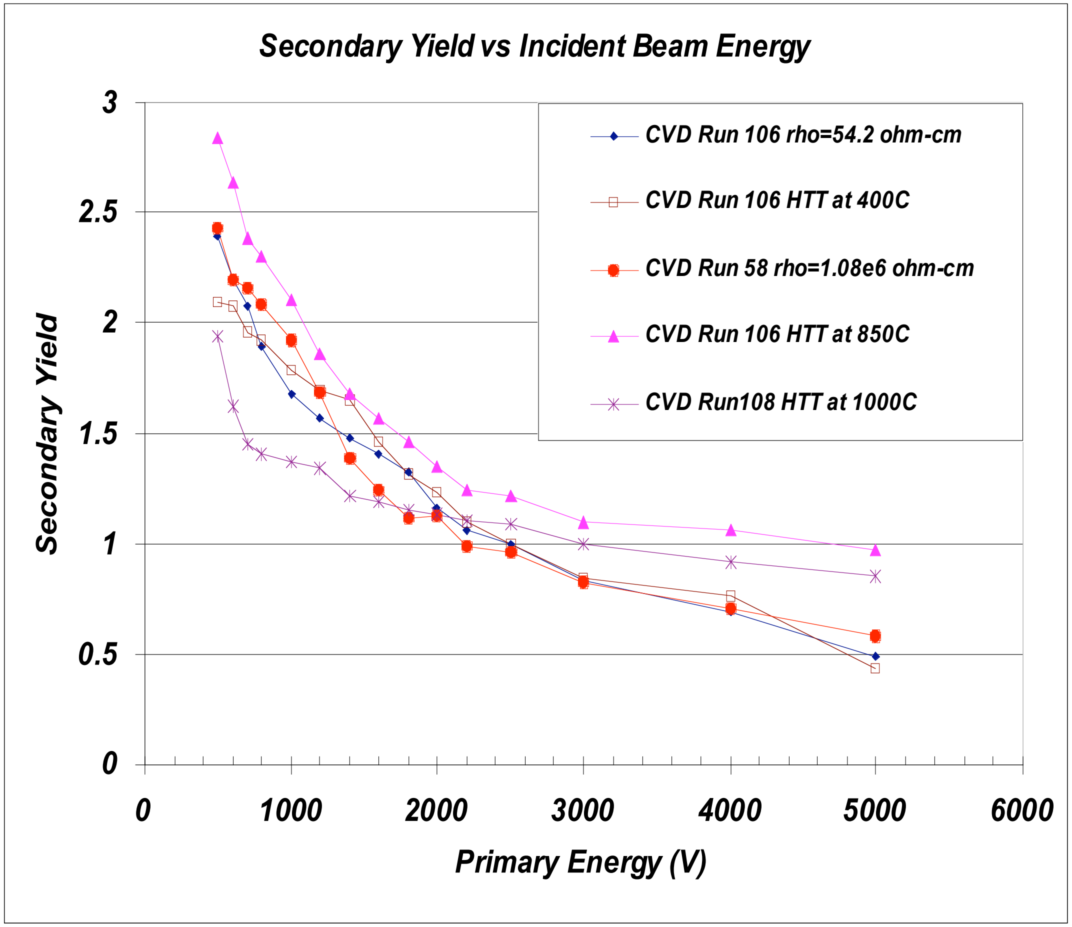
<- SiMCP converted entirely to SiO_2 by steam oxidation - transparent.

- **Full Nitriding (Si_3N_4) and Carburizing (SiC) are also possible.**

-> Many Applications

Towards a SiMCP



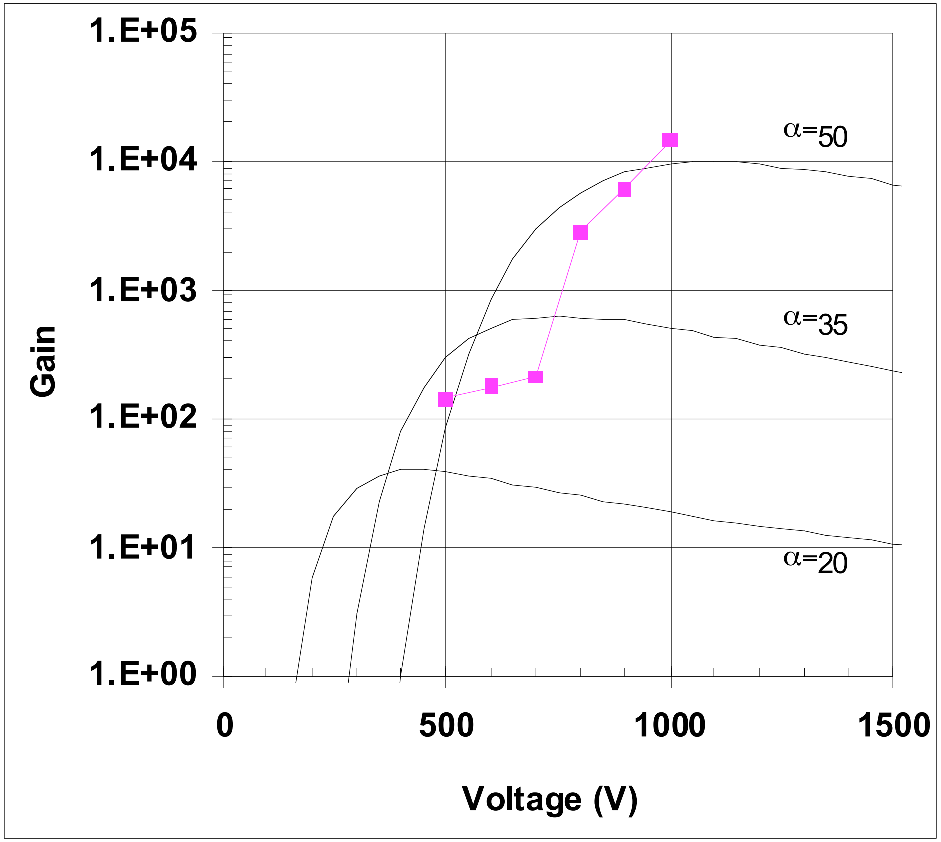


Flow through CVD SE coatings remarkably uniform

Si-rich SiO_2 SE negative T-coefficient of R a problem

Much better SE/Controlled conductivity films possible

SiMCP - Gain



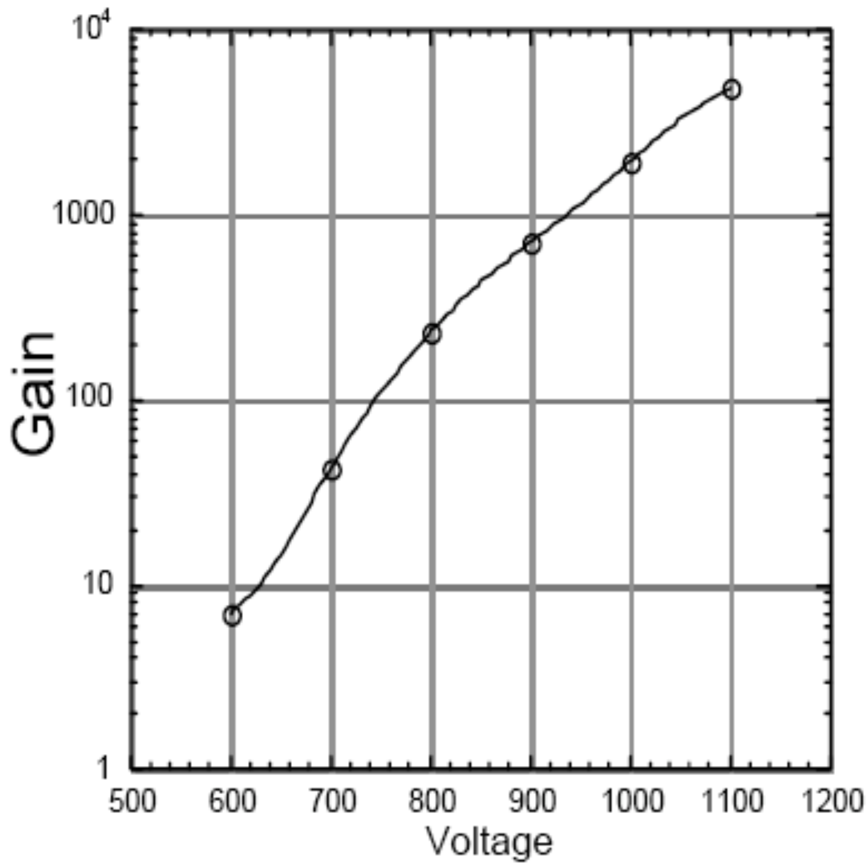
$G = (AV/2\alpha V_o^{1/2})^{\gamma}$

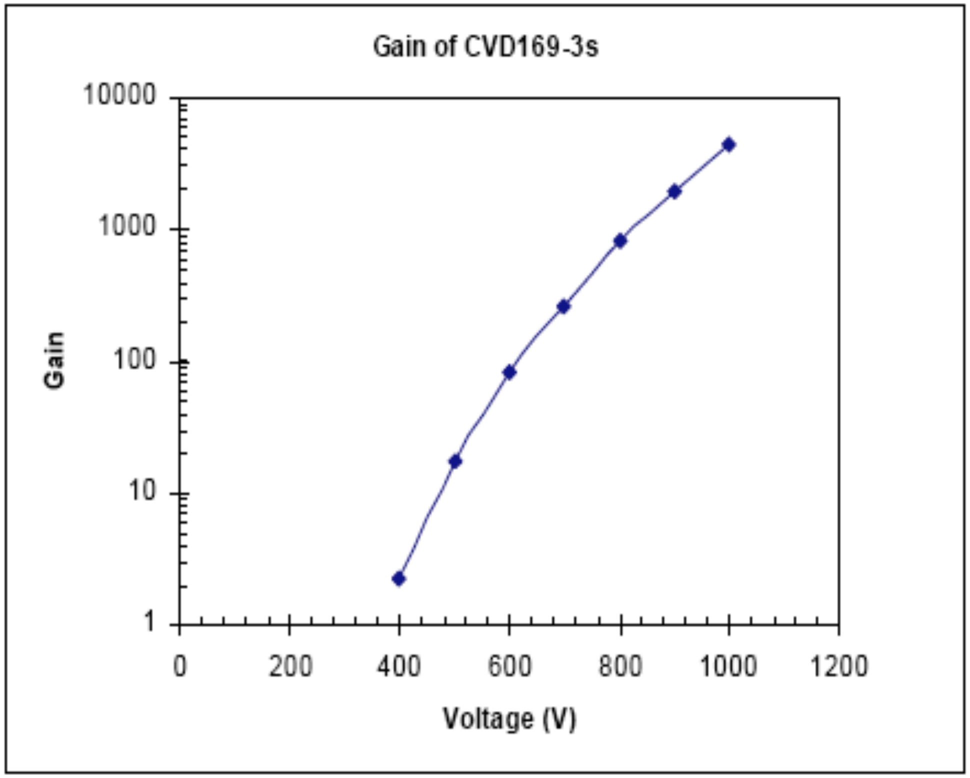
$\gamma = 4\alpha^2(V_o/V)$ V_o:secondary electron energy

A: SE yield data $\delta = AV_c^{1/2}$

α = channel aspect ratio = L/D

SiMCP Gain - II





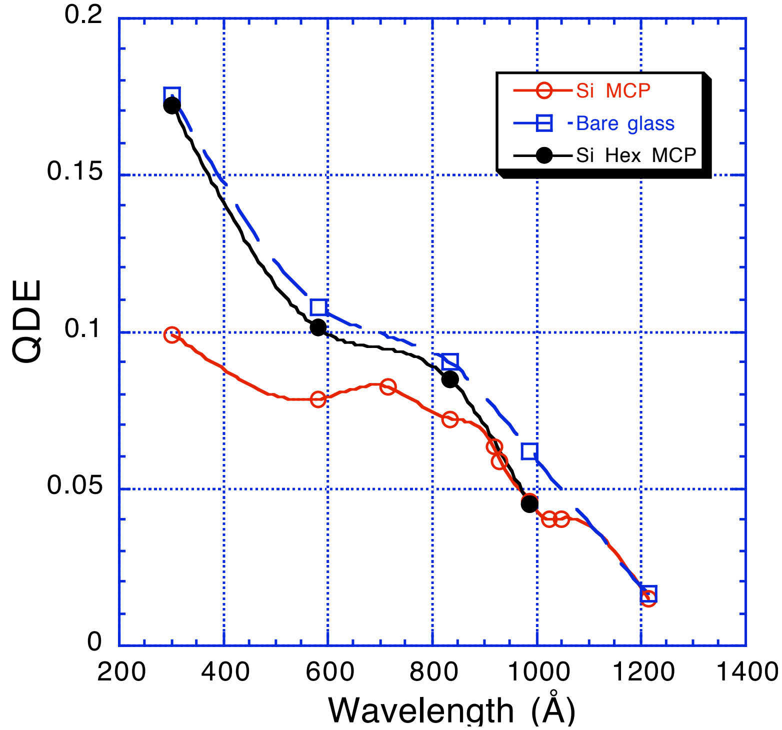
40:1 aspect SiMCPs

Left: Hexagonal Channels - Right: Square Channels

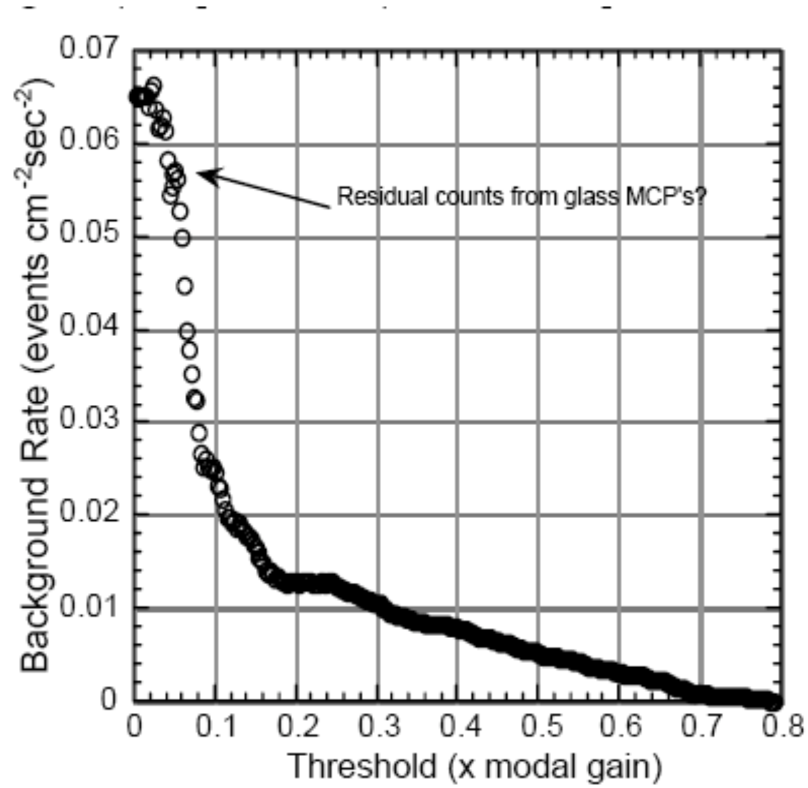
Gain ~ 6,000 at 1,100 V per plate

SiMCP Properties

Shape Dependence



Self-Counting

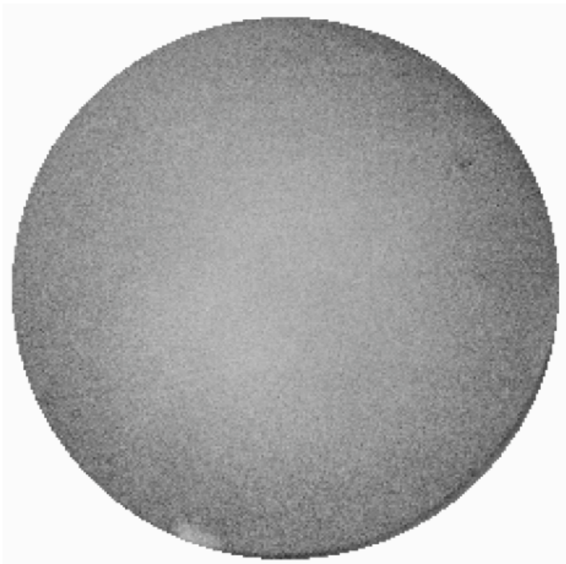


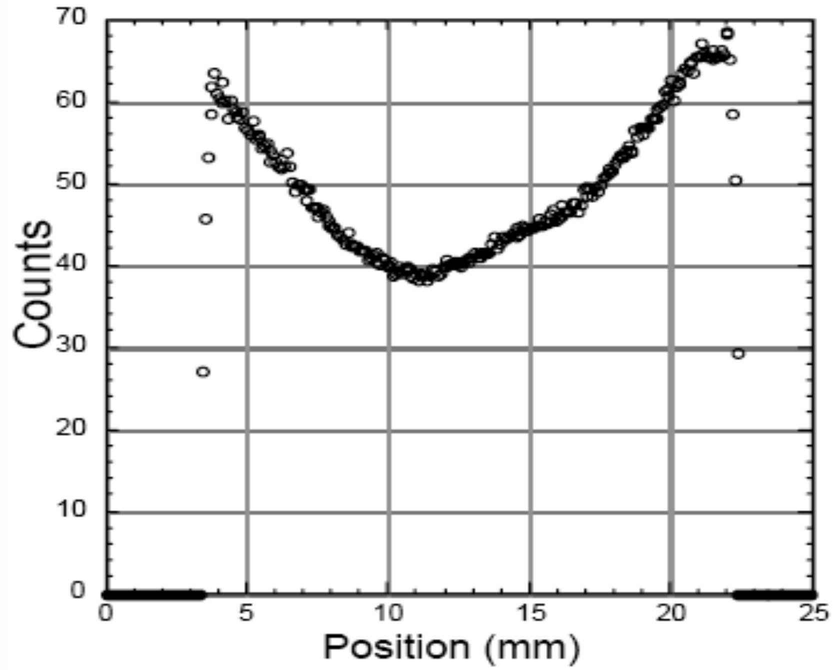
SiMCP background rate(SiMCP mounted above pair glass MCP's). Glass MCP: Rb, K radioactive isotopes ->

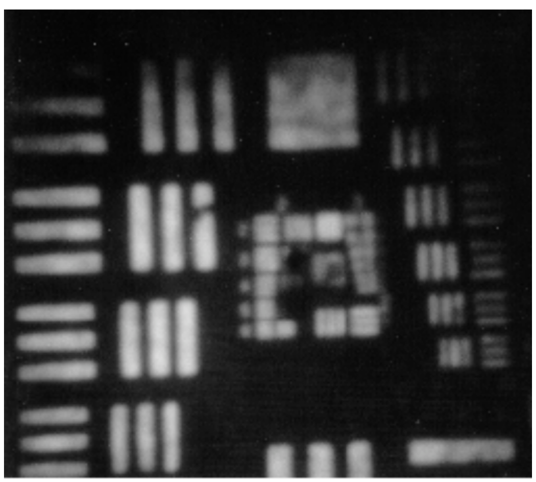
Glass MCP Backgrounds: 0.25 - 1 events cm^{-2} sec^{-1}.

Si MCP Backgrounds: ~0.02 events cm^{-2} sec^{-1} (10%)

SiMCP Precision







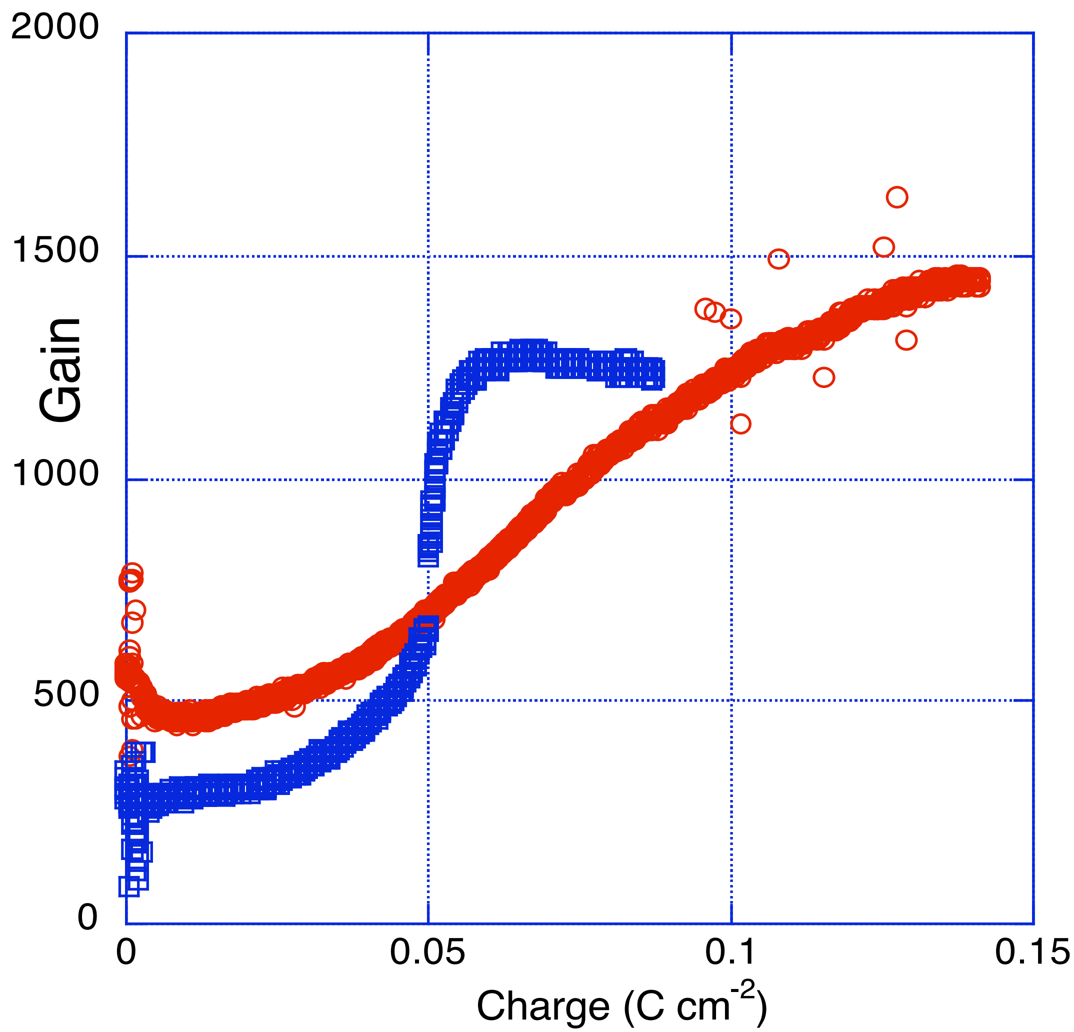
- Flow Profile during SE coating CVD

->Electrode Resistance

>100 lp/mm - contrast w/ glass MCP

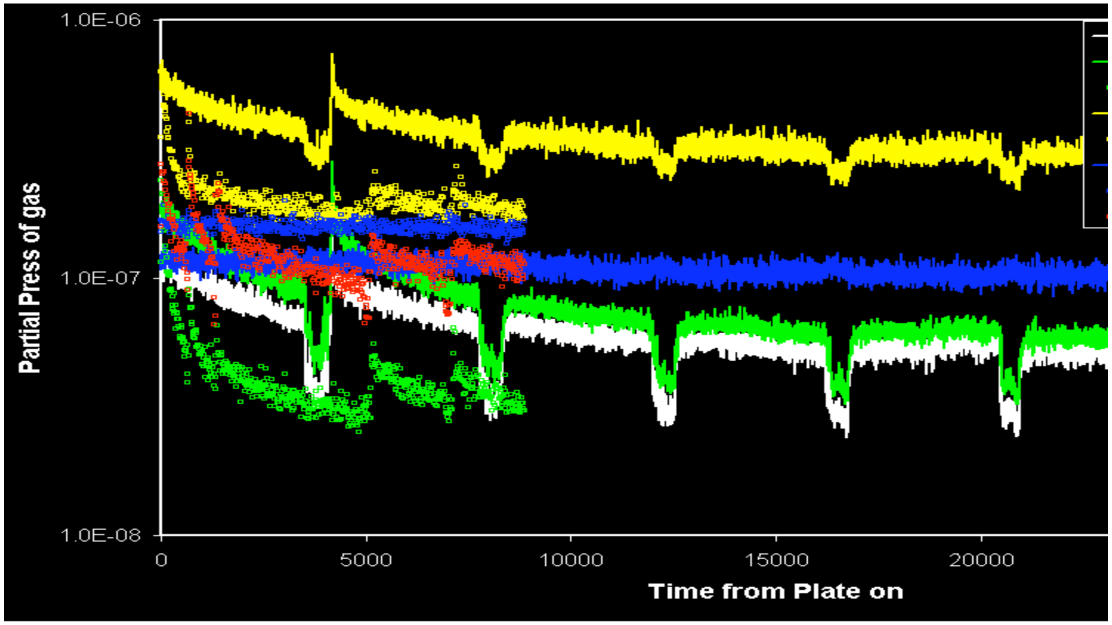
SiMCP Lifetime

2 SiMCP

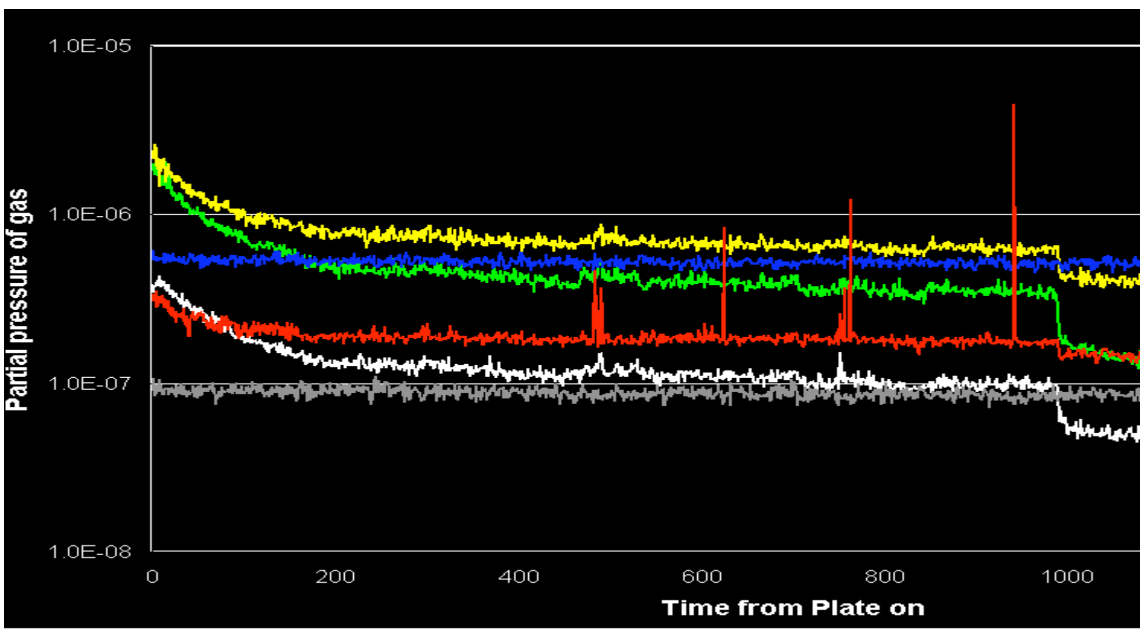


SiMCP Gain *Increases* with operation (C/cm^2)

SiMCP Lifetime -II

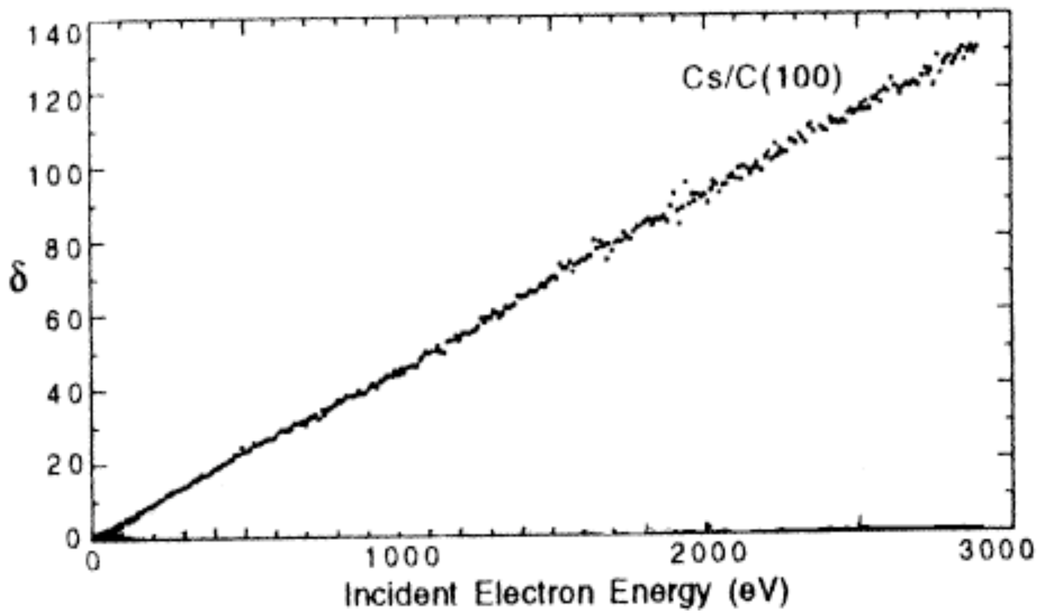


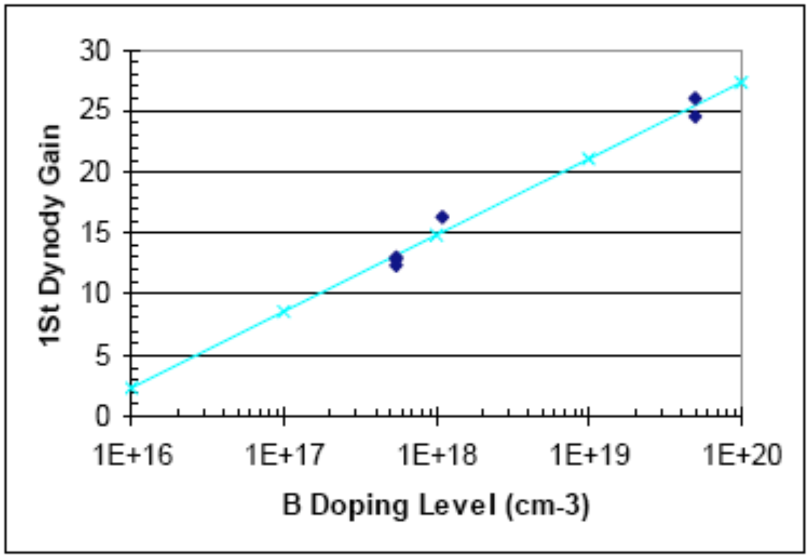
Glass MCP
Outgas:
~15,000 sec



SiMCP
Outgas:
<500 sec

Diamond Secondary Yield

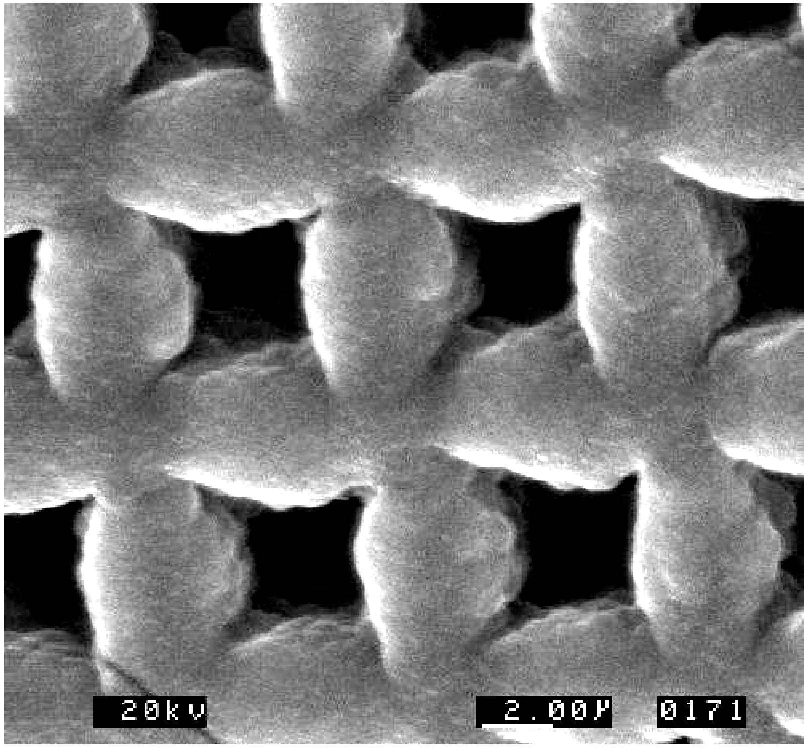


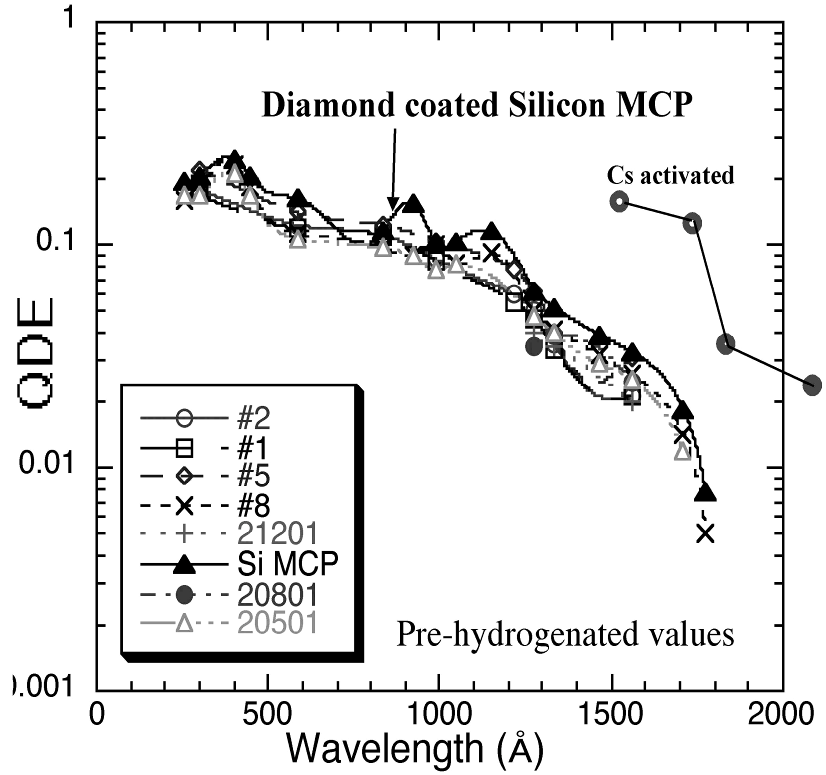


Left: C:Cs secondary yield;
Right: 1st Dynode Gain vs B-doping 400 Volts K-D1

High secondary yields->10% single p.e.resolution

SiMCP/Diamond





- CVD Polycrystalline Diamond -
- Pseudo-Lattice Match to Si
- Deposited on SiMCP by
  CH4/H2 decomposition 10 Torr

SiMCP Hype

Large Area/low cost - 30 cm wafers [Glass ->$$$]
leverages VLSI, OLED, Plasma/LCD Technologies

Photolithographically Precise - [lp/mm ~ channel size]

Compatible w/ Photocathode, SE, refractory materials

Long Life - can go to air - negligible oxygen, water

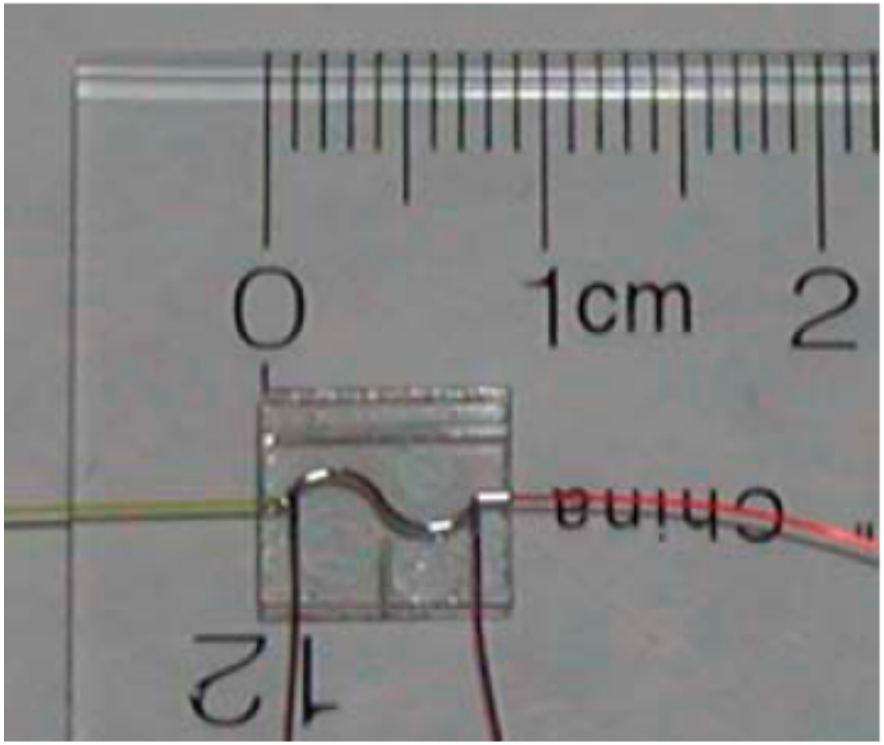
Ultra-low intrinsic background

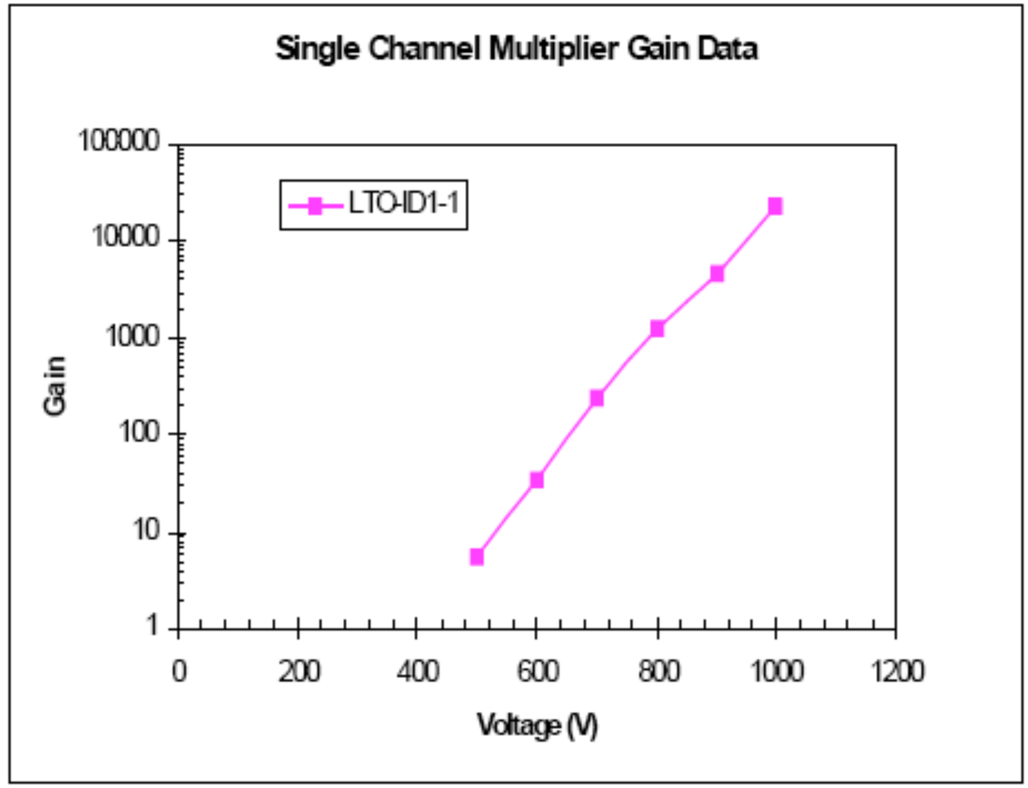
Integrateable schemes with Si readout electronics

High Axial B configurations (photocathode in throat)

- **12" diameter x <1 cm thick "dinner-plate" PMT**
Self-supported window, PCathode deposited in Channels

Quartz MicroMachining



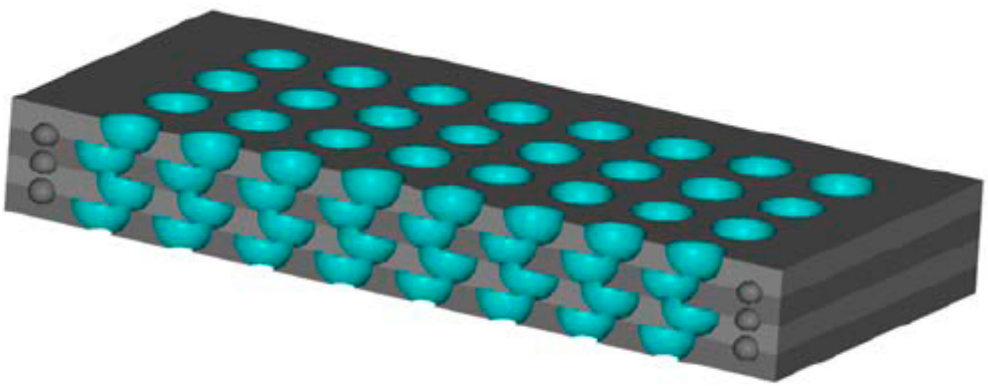


Low Noise Single Fiber Optic Receiver

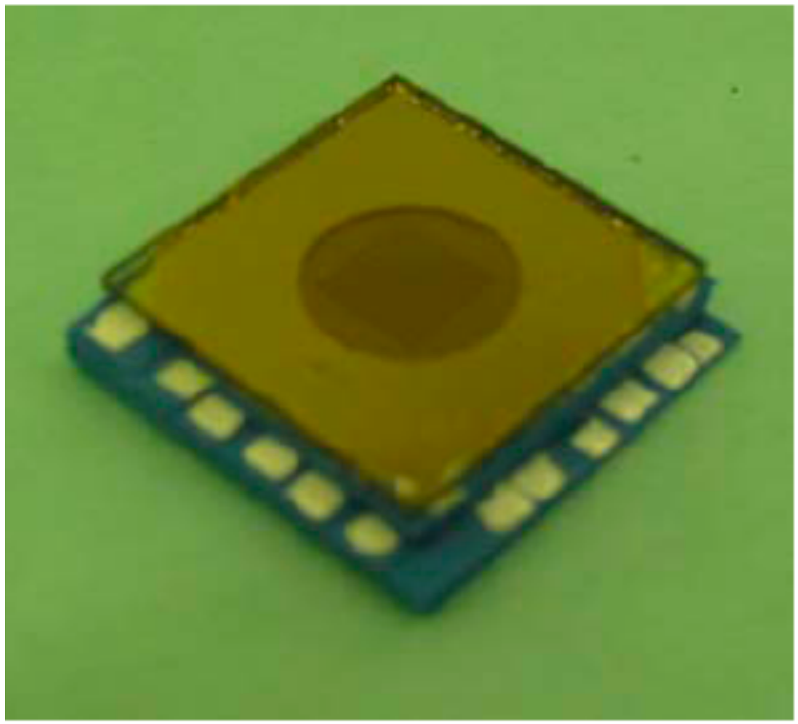
-Continuous S-dynode, 200 µm fiber input

- *Gain ~22,000 at ~1KV*

SiMicromachining - MicroDynodes

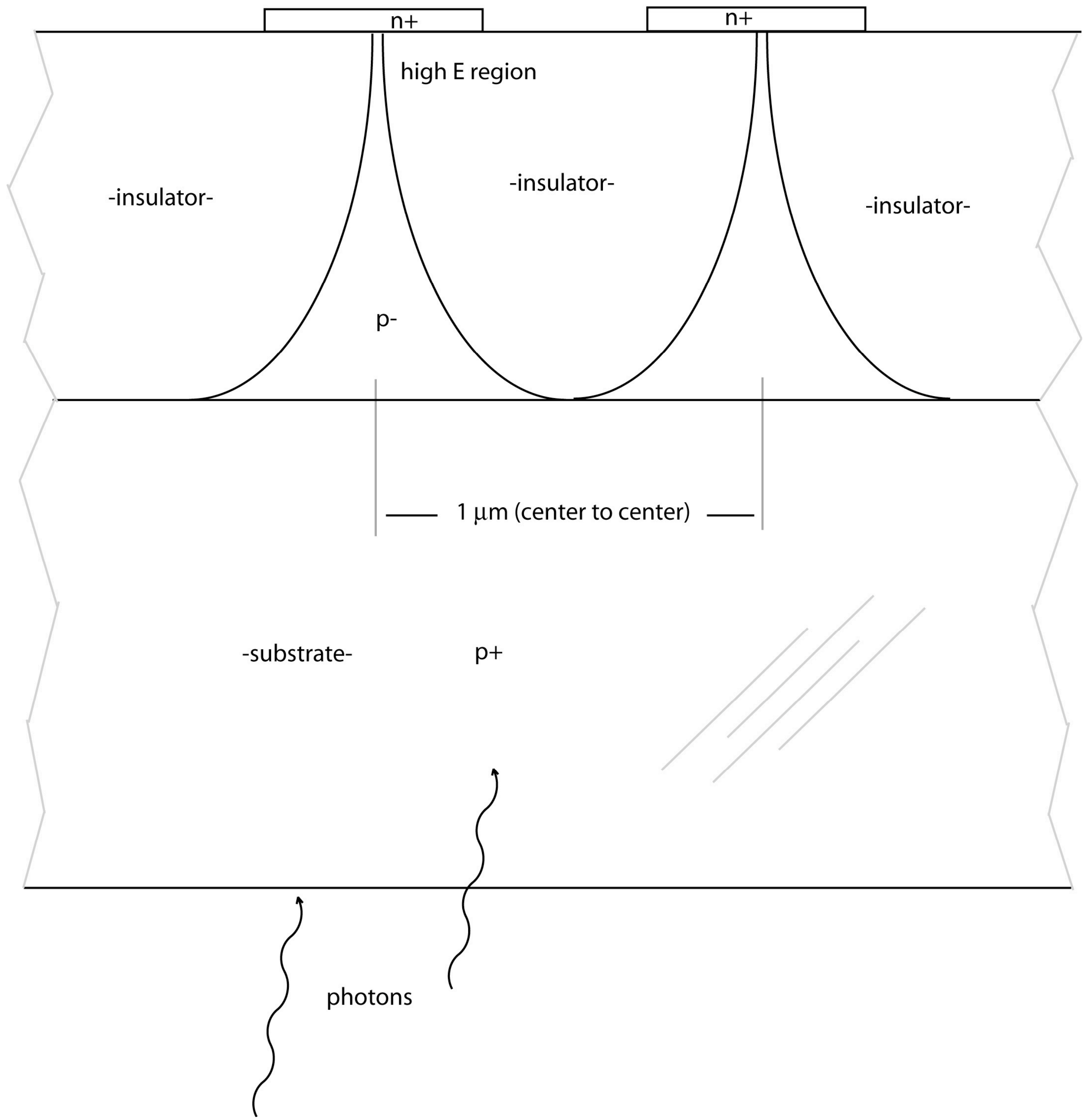


Self-aligned stack “teacup”
Dynodes, 50 μm Si wafers

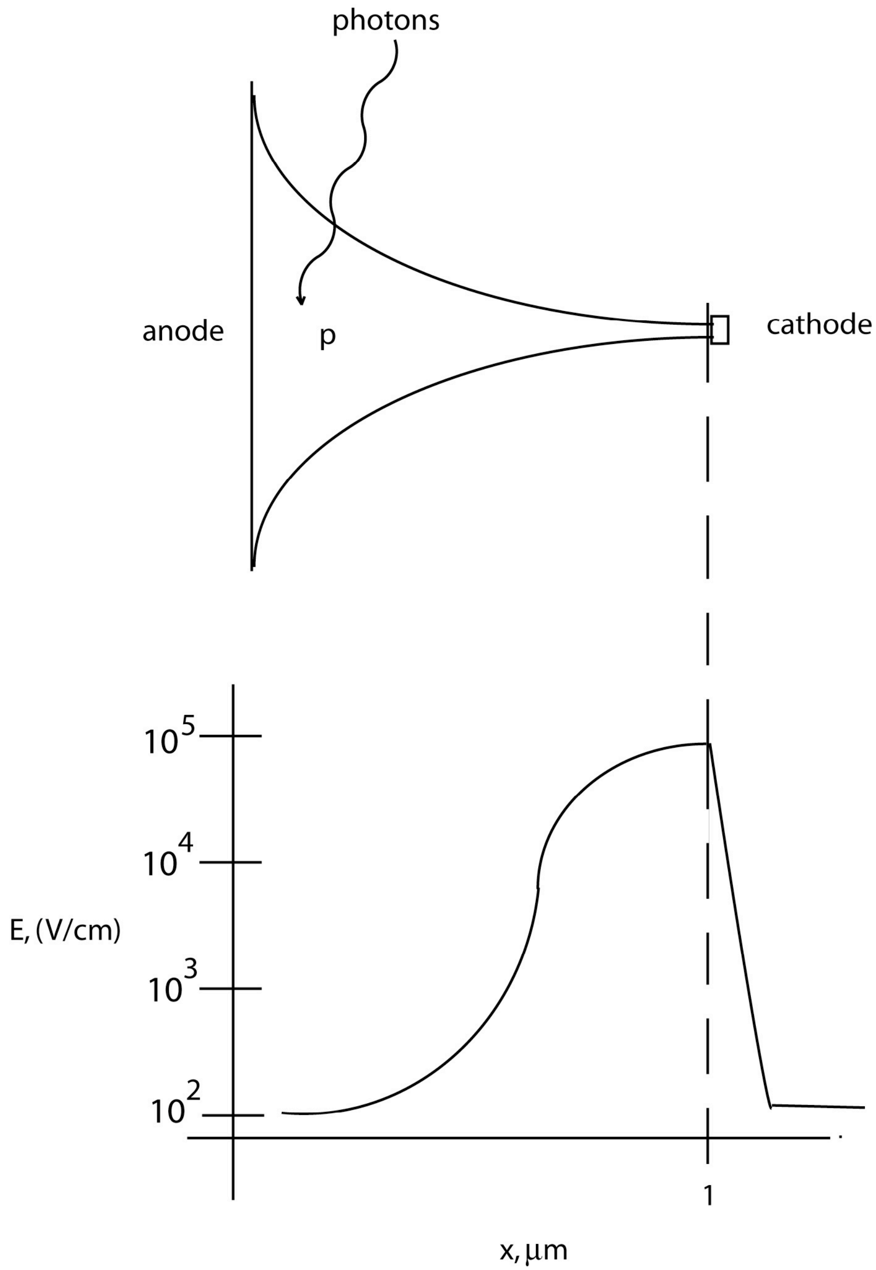


8 stage microdynode PMT prototype.
ceramic body, 1x1 cm active area

Towards a GAPD Pixel Array



G-APD



CONTROL:

- **Length of High field region**
- **E-field size/shape/taper**
- **Precise control of size of E**

Benefits:

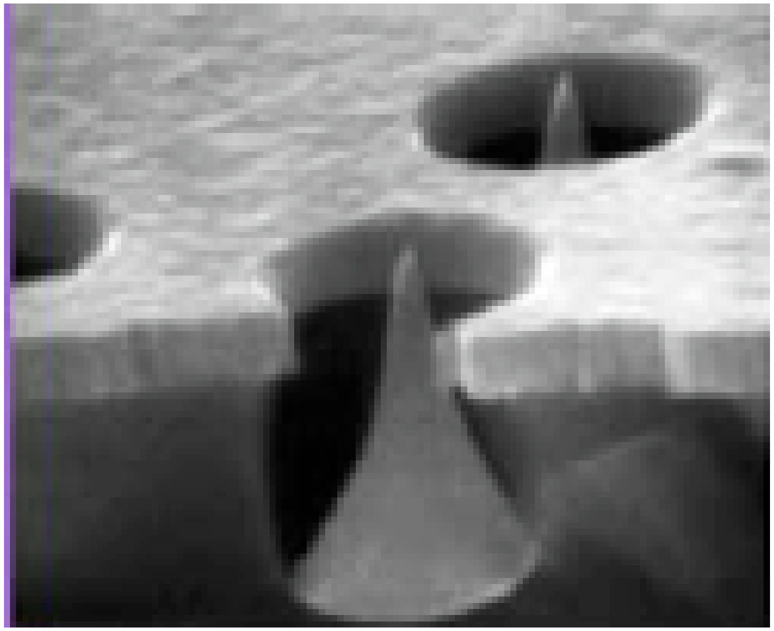
a) Less Noise:

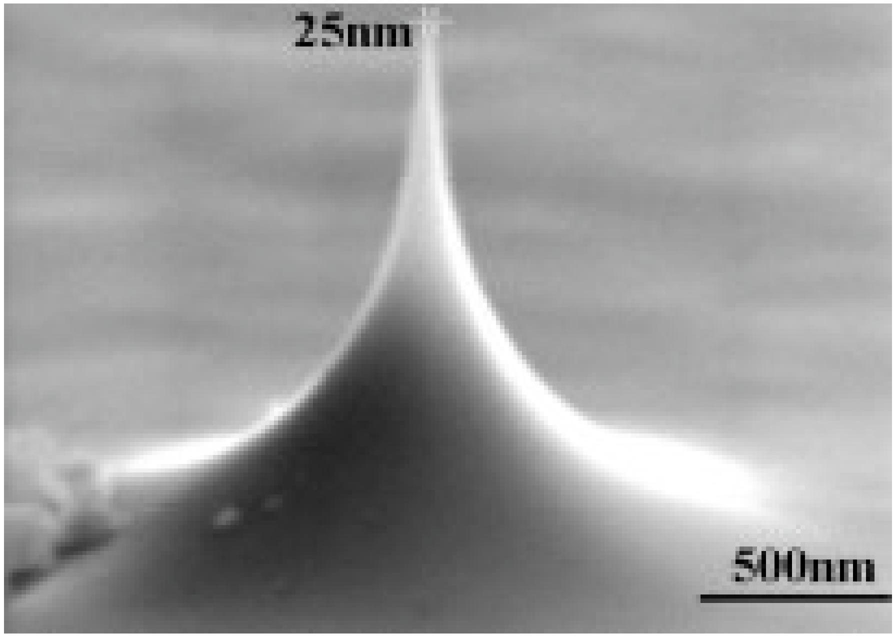
- **Lower interband Doping**
- **Less high field Si volume (x 100-1000 less)**

b) Proportional Gain

Towards a Geometric APD

leverage field emitter tips



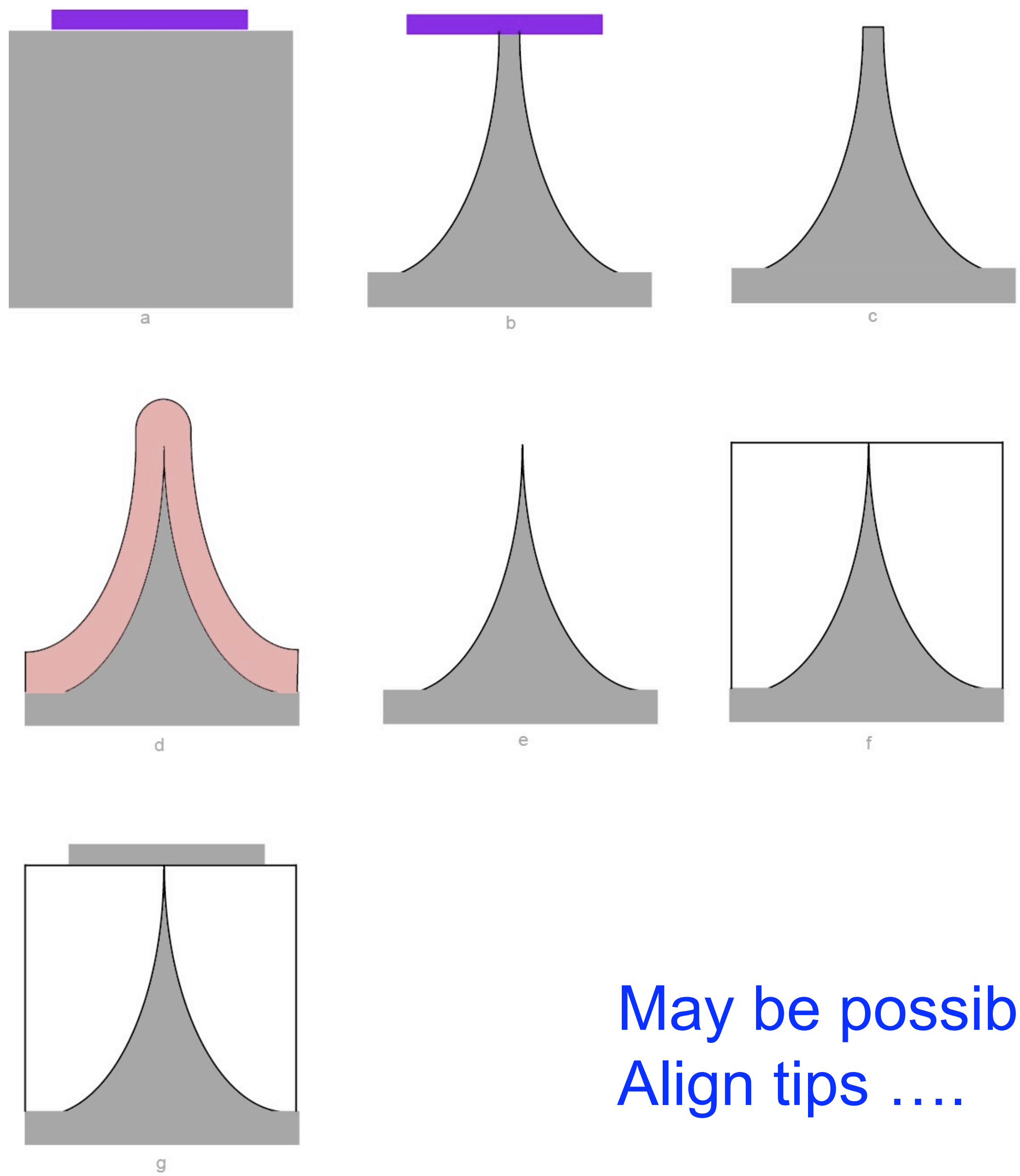


Standard Monotonous Patterned Nanomachining:

- Controlled isotropic chemical etch
- Anisotropic electrochemical etch
- Photoelectrochemical etch
- Others……

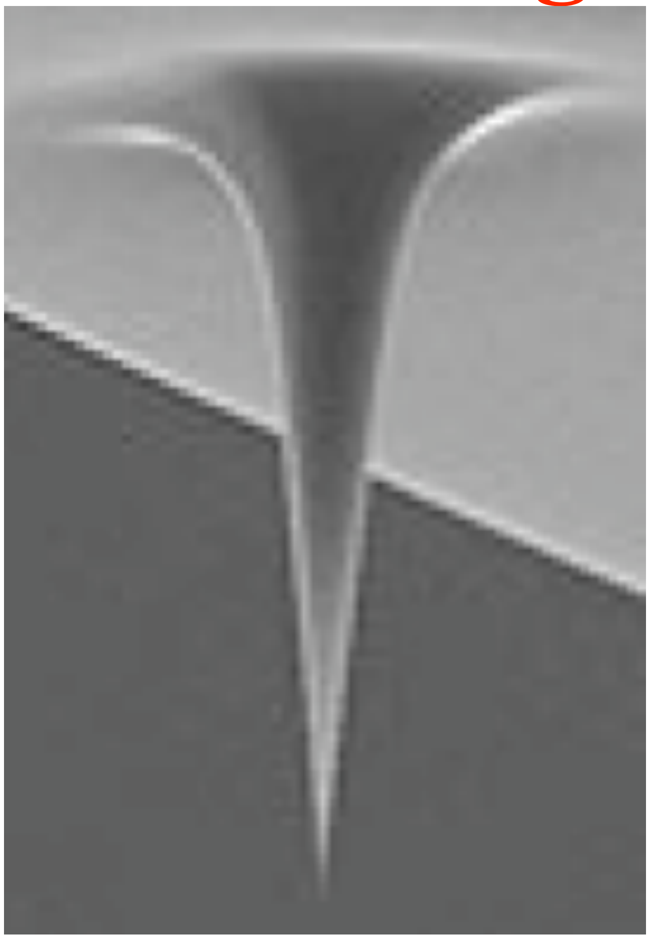
~Analogous to “Field Emitting” back into silicon

Isotropic Etch Example



May be possible to top/bottom
Align tips ….

Single Pixel Tests



- Tips from STM/AFM manufacturers
- Modify tips (and lever) to suit (thin top Si)
- Insulate or strip-off insulation, deposit transparent electrode/s
- Use AFM/STM to assemble to the opopposite doped Si

Single Pixel Tests

- p-Type AFM tip, ~50 micron base x ~250 μm long, insulated ~20 nm Si3N4 except tip, metal annulus contact
- Tip placed by AFM to the surface of polished thin n-type Si wafer, metal ohmic back connector.
- Direct/Anodic bond - few μs HV voltage pulse.
- Reverse Bias, intensity I~400,000+/-10% green photons/s 40 micron core optical fiber on back annulus.

- **40 V, G>200, assuming QE 50%.**
- **30-80 V & I->3I: Gain ~ linear within 20%**
- **90~110 V, draws large current, Geigering.**
- **>110 V failed (Heating? Electromigration?)**

Light Amplifier\
(Phase-Space) Compressor
Photodetectors:
LA\C Tubes For
Astroparticle, Neutrino, and
HE Physics

PRINCIPLES:

- PHOTONS ABSORBED ON VACUUM PHOTOCATHODE LOSE MEMORY OF DIRECTION – **Allows p.e. phase space compression**

- THE DIRECTION OF PHOTOELECTRONS ABSORBED IN A PHOSPHOR or SiDiode MAKES ~NO DIFFERENCE IN LIGHT OUTPUT or EBS Gain (UNLIKE SE ELECTRONS FROM DYNODES)

- WAVELENGTH-SHIFTER TECHNIQUES EFFECTIVELY SAMPLE LARGER AREAS AND COMPRESS PHOTONS IN A SMALLER AREA x ANGLE PHASE SPACE

The Overall Idea

• Image-intensifier-like tube (various geometries):

  • Photoelectrons accelerated to HV. Initial p.e. angular/energy phase space relatively unimportant.

  • Photoelectron image preservation unimportant (Winston Cone analog – trade Solid Angle<->Area).

  • (Demagnified) p.e.image ->fast phosphor (or SiDiode) “screen”.

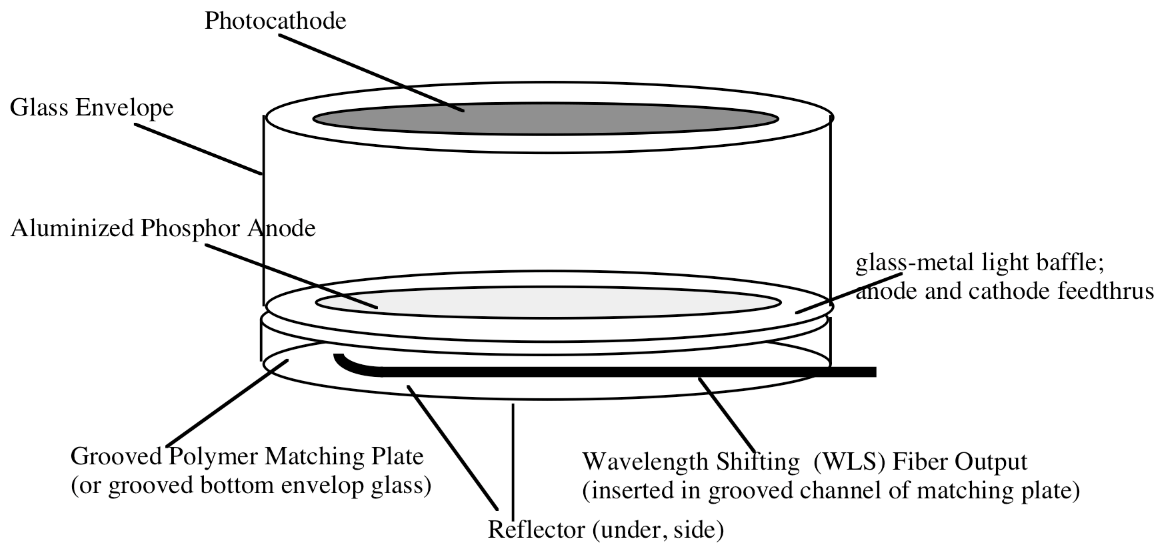
  • Phosphor light output collected by wavelength shifter fibers or bars, or directly by a much smaller photosensor.

• Photoelectron spatial phase space can be compressed in:

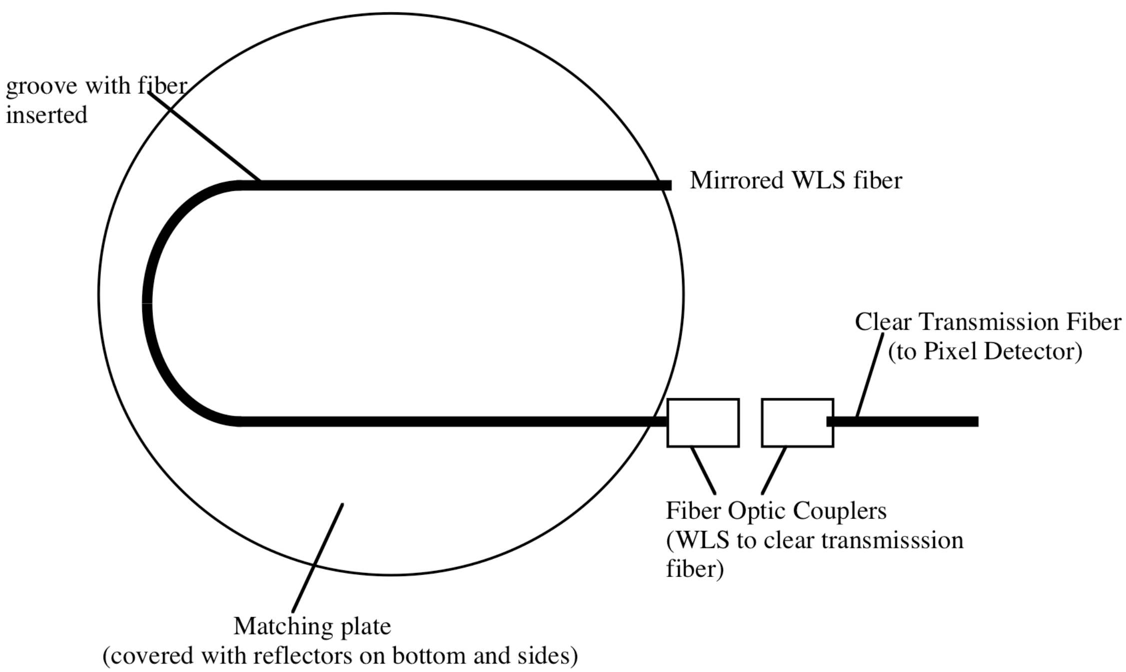
- 2 dimensions (sphere),
- 1 dimension (cylindrical geometry), or
- 0 dimensions (plane-to-plane) – photon compression by WLS

• Photon Gain is given by phosphor efficiency and HV.

• Speed given by phosphor decay and isochrony of phase space compression.



O-Dimension
p.e. Compression:
Proximity Focused
Phosphor Anode,
Wavelength Shifter
Optical Fiber Output



Since no image,
Posts can be used
To support cathode-
Anode spacing –
Large Tubes possible

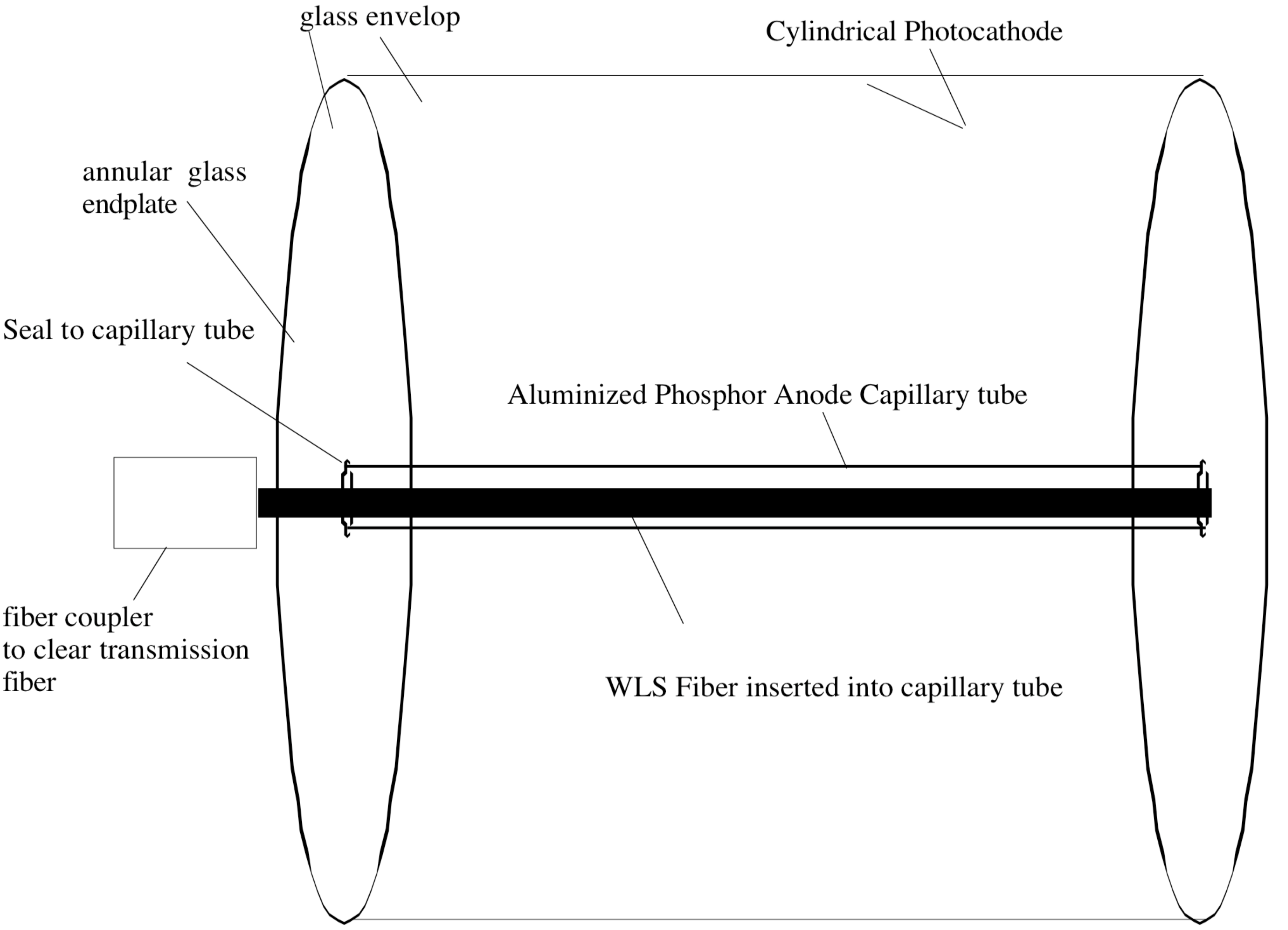
Phase Space Compression Factor K: product of ratios of areas and angles of photocathode and the fiber:

$$K = (D_{pc}/D_f)^2 \text{ x } (\sin\theta/\text{N.A.})$$

- **K can exceed 10,000 with typical values**
- **Standoff Voltage: ~5-10kV/mm**
- **Compact along axial direction < 1cm**
- **Excellent in axial magnetic fields – photoelectron direction on phosphor makes little difference in light output**

1-D p.e. compression: Cylindrical Geometry – Radial Focus

Scales to long lengths



Cylindrical Photocathode Scaling:

High Aspect Ratio:

Minimizes (vacuum volume/PC area)

Examples:

- Scintillator "edge" detector
  5 mm diameter x 100cm long; 300 μm fiber output

- Large Cosmic/Neutrino/Proton Decay:
  10 cm diameter x 3 m long – 1 mm fiber output
  (Think: "fluorescent tube: aspect ratio)

- Complex energy-flow calorimeter
  Ultra-compact, no-base tubes 1 cm Dia x 1 cm long

Cylindrical Phase Space Compression:

Photoelectrons emitted at radius R will cross an anode of smaller radius r given by:

$$r \sim R(Epe/V)1/2$$

Epe: photoelectron energy (~0-2.5 eV)

V: K-A voltage in Volts

Areal compression = Acathode/Aphosphor =

$2\pi RL/2\pi rL = R/r = (V/Epe)1/2$

(L=cylinder length)

Examples: Areal Compression ~200 at 40kV (Photocathode area/PhosphorAnode area):

5(2") cm dia cathode, 300μm diameter phosphor anode

12" (30 cm) dia. cathode, ~2 mm dia phosphor cylinder anode.

Feature: **readout by small photosensors from both ends of the fiber allows "Light Division" localization of centroid of the incident light.**

Phosphor Anodes and Photon Gain

photon gain per photoelectron

Best Rad-Hard Fast Phosphors

ZnO(Ga),, (0.4-0.75 ns decay, 40-60 photons per KeV – up to 1.5 times NaI, 390 nm peak wavelength) ,,.

CdS:In 525 nm peak emission, <1 ns decay to 10%,50% NaI

Nanocrystalline phosphors < 50 nm in diameter, Tdecay <1 ns, energy efficiencies > 50%.

ASIDE! Use ~10 nm powders with surfactant at concs to give ~ 1 nanoparticle/mm of track in dihydrogen oxide-based prot -rot detectors (~50 T/megatonne of water)

Nuclear Enterprises Catalog (1978).
Levy-Hill Lboratories, Tamarac, FL
Sigma Chemical Corp.
W. Lehmann, Solid State Electronics 9, 1107 (1966)
D.Luckey, Nuc.Instr. and Meth. 62, 119 (1968)
S. Derenzo, W. Moses, Proc. Crystal 2000, Chamonix, FR (Sept. 1992)

Phosphor Film Thickness: < 5 microns up to ~50 KV

Photoelectron Penetration Depth T (μm)

$$T = 1.1 \times 10\text{-}6\ V_b^{1.4}\ \mu m$$

- V_b incident electron (photocathode-anode) V
- 50 KeV: electron range ~ 0.001 g/cm2 .

Aluminum-Coated Anode:

- Al film thickness 50-80 nm (OD ~ 11)

~400-700 eV lost to the aluminizing

reflectivity factor light gain 1.8-1.9

Photon gain g per p.e.: 18-55/KeV

E.Kobetich, R. Katz, Phys.Rev. 170, 398 (1968)

Phosphor Anode Formation

(i) Powder Films: standard settling binder technique
(fine phosphor powders dispersed in a silicate solution binder,
which adhere to the item to be coated,
which is then fired at moderate temperatures),

(ii) PVD Films (e-beam evaporation preferred),

(iii) Microwave ECR Argon Sputtered Films

(iv) MOCVD Films

For a brief review of phosphor screen technology,
see sections 11-60 to 11-72 and references therein, of the
"Electronic Engineers' Handbook", pages 11-33 to 11-40,
1975, McGraw Hill, NY

Total Photon Gain G:

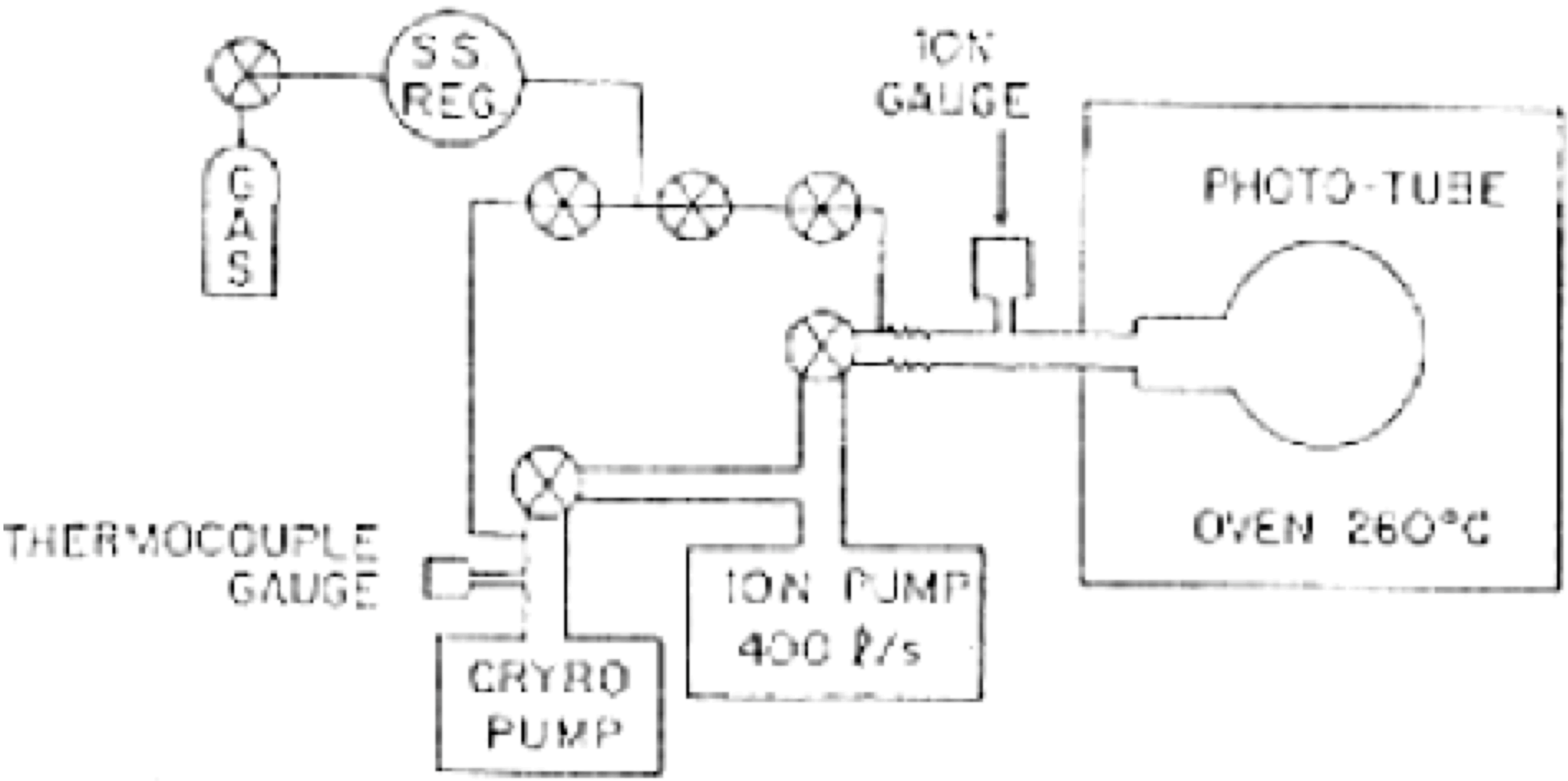
G photons captured in an output fiber per incident photon on the photocathode is given by:

$$G \sim Q\, e_k\, V\, g\, e_c\, e_f$$

Q: quantum efficiency of the photocathode,
e_k: average p.e. collection efficiency
V: anode-cathode V, corrected for Al losses;
G: phosphor light emission photons per Ep.e.,
ec: capture efficiency of the produced light
(Anode Al mirror, n mismatches, phosphor self absorption)
e_f: acceptance of the fiber (numerical aperture).

Example:
Q=20%, e_k=90%, 40-50 KV,
g=35-55 photons/KeV e_c=50%,e_f =4%:
G ~ 4-7 photons captured on a fiber per incident photon.

Photocathode Deposition Schematic



PhotoCathodes and Cathode materials:

The basic techniques for photocathode fabrication:

a) Exceptionally clean conditions

(stainless steel and glass, extensively baked out Sb 99.99999, etc);

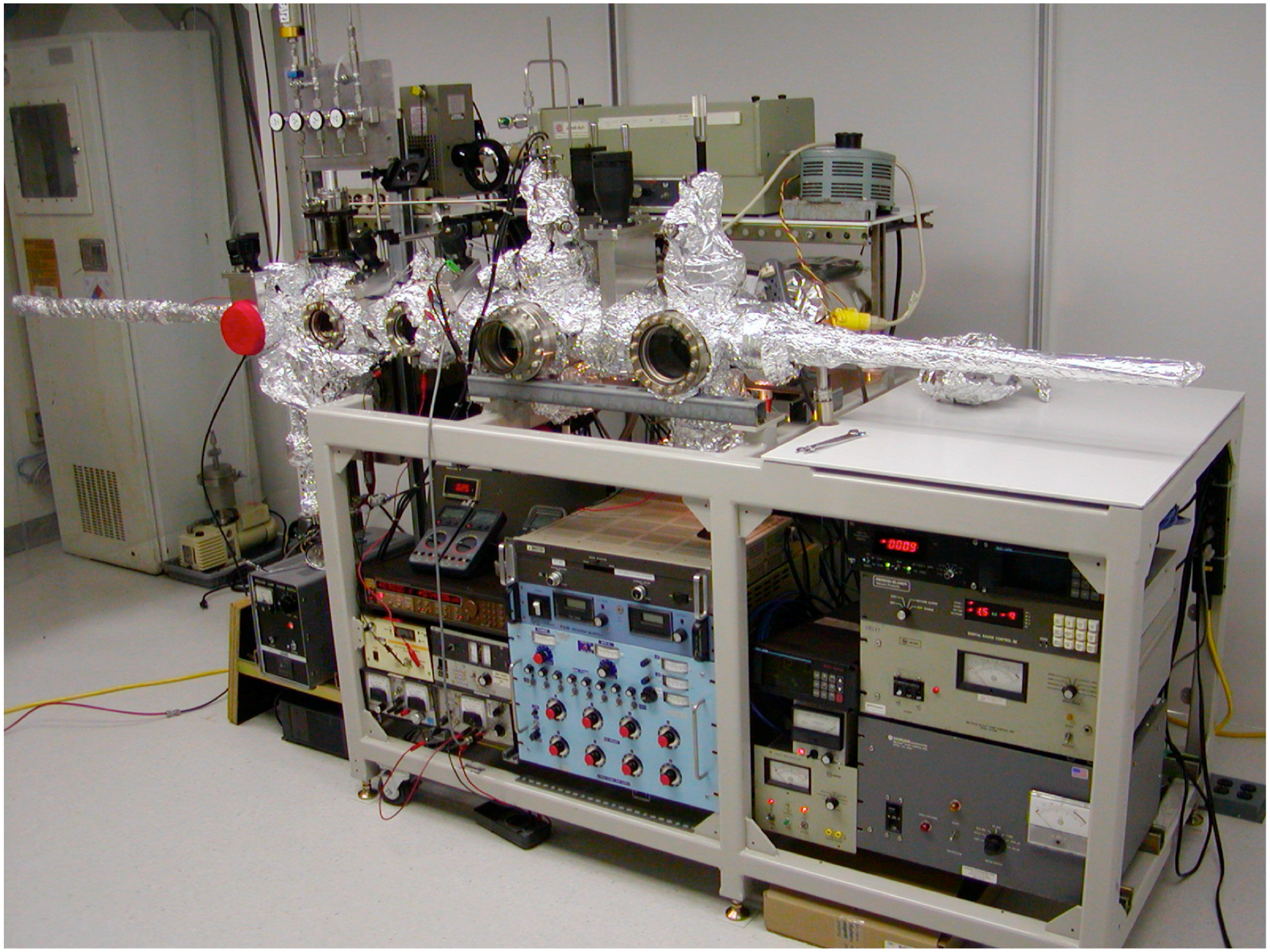
b) High capacity demountable high (10^{-10}) vacuum system;

c) *Controllable* Deposition Oven capable of 400°C; Sb layer, typically 10-20 nm, thick for a semi-transparent cathode (3-4 μg/cm2 of Sb) – **ACHTUNG!** *MEB, Flood Coevaporation, micropatterning/diffusive/reflection of cathode substrate*

d) glass-blowing and/or -sealing techniques

for initial fabrication, connection to and final pinch-off of the device from the vacuum rig after fabrication, at low enough Temperatures ($T<300^{o}$)

PMT Assembly and Photocathode Transfer Station

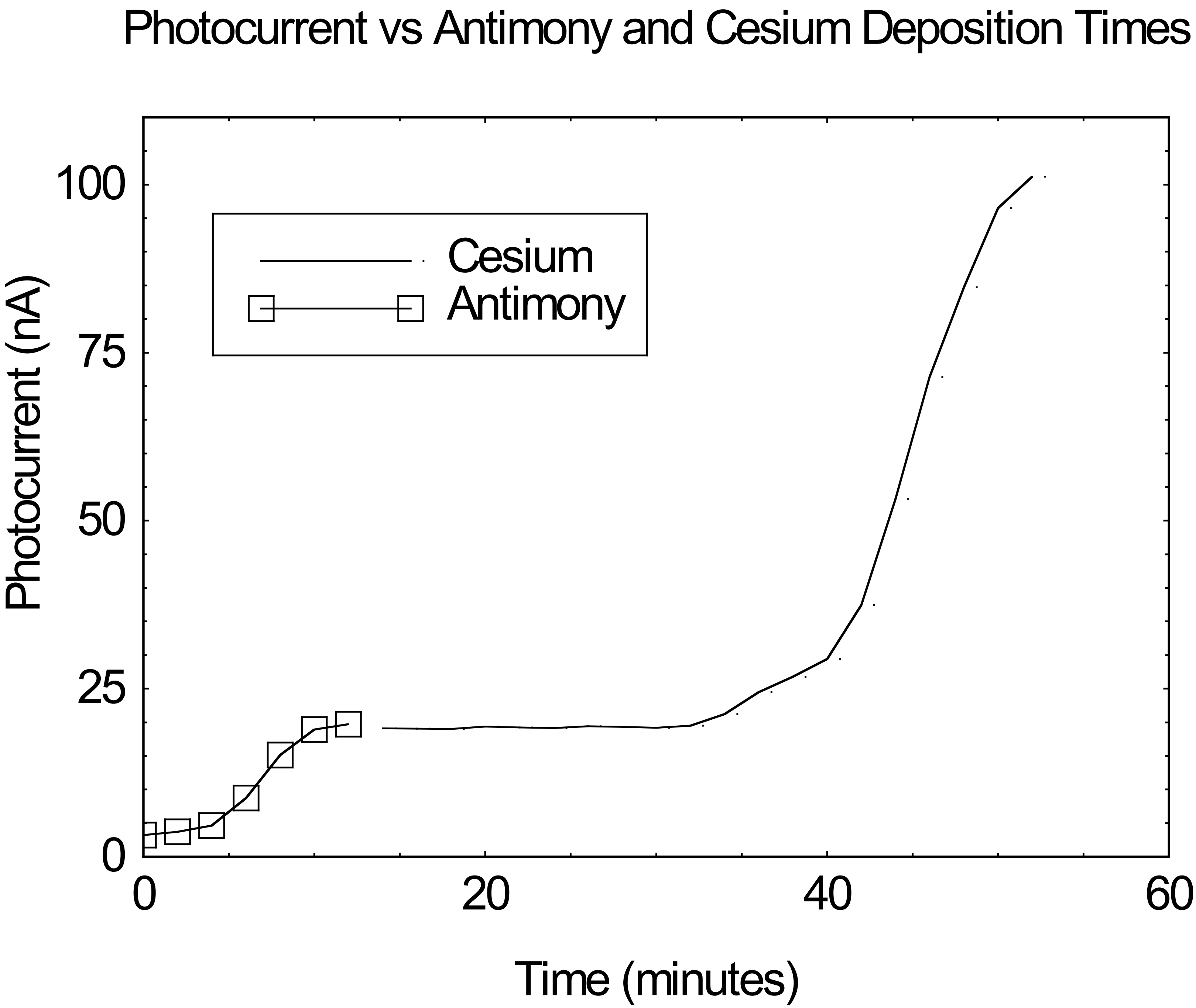


Processing station used for assembling PMT from a vacuum transferred photocathode and assemblies.

From left: monochromater, Kelvin probe, photoemission, sample introduction, sealing, and photocathode transfer.

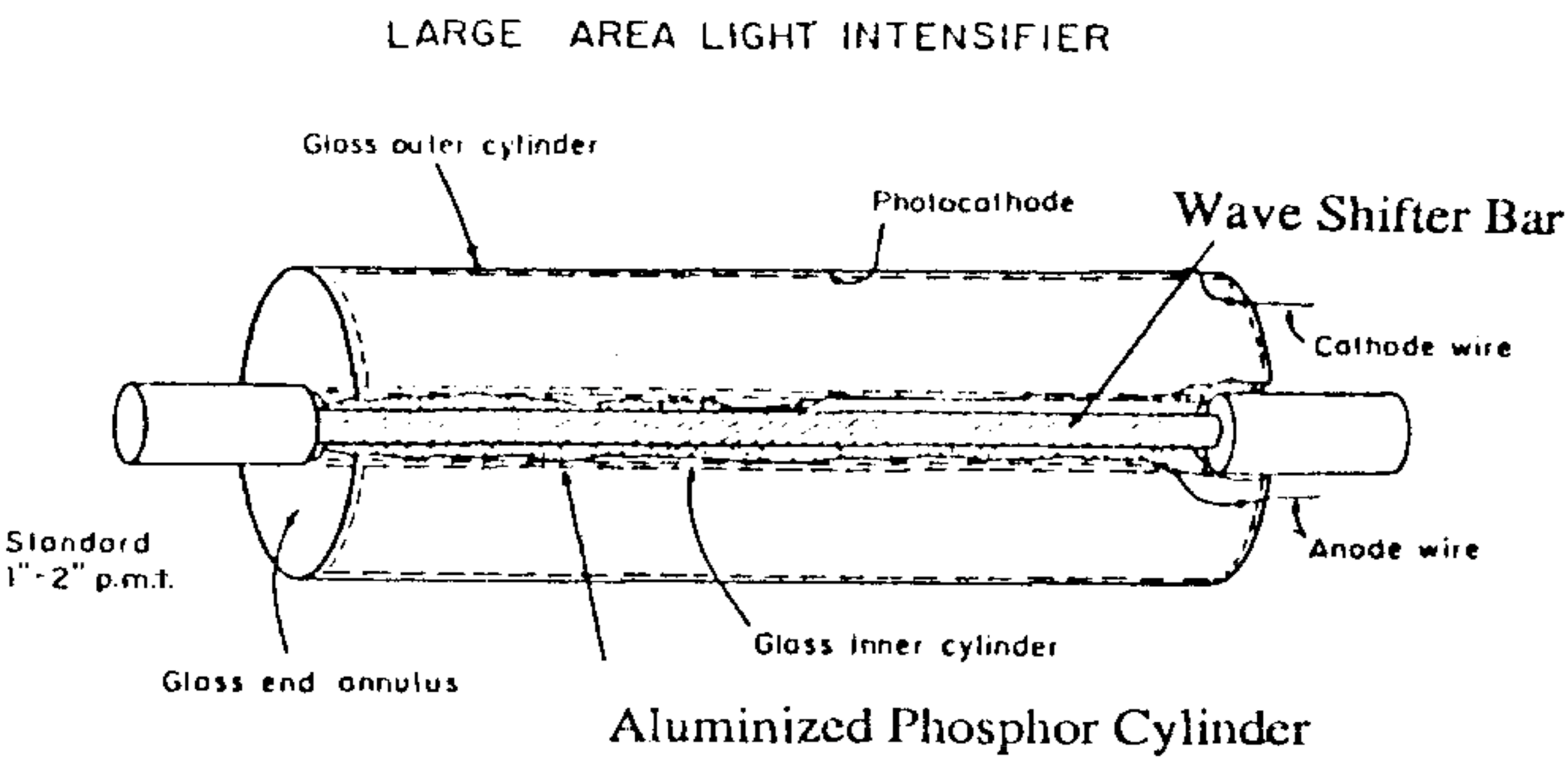
Photocathode Processing Equipment

for loading into a vacuum shuttle to the PMT processing. Precision flood coevaporation results in a better quality photocathode than interdiffused in situ

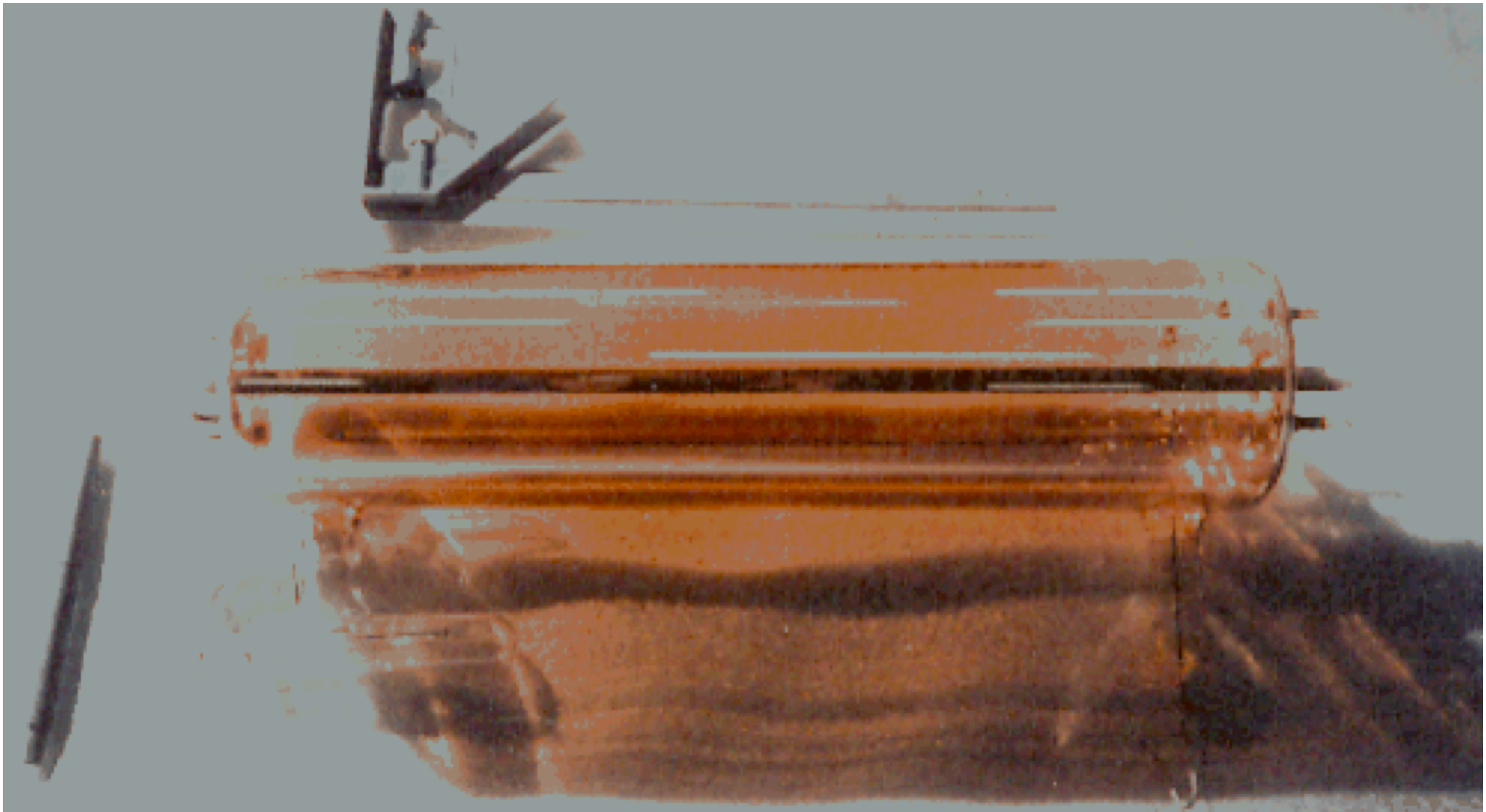


Photocurrent vs Antimony and Cesium Deposition Times
Photocurrent (nA)
100
75
50
25
0
0
20
40
60
Time (minutes)
Cesium
Antimony

Cylindrical Prototype:



Half-mirror back+thinner xparent photocathode deposited ->> higher QE



Cylindrical Light Amplifier/Compressor

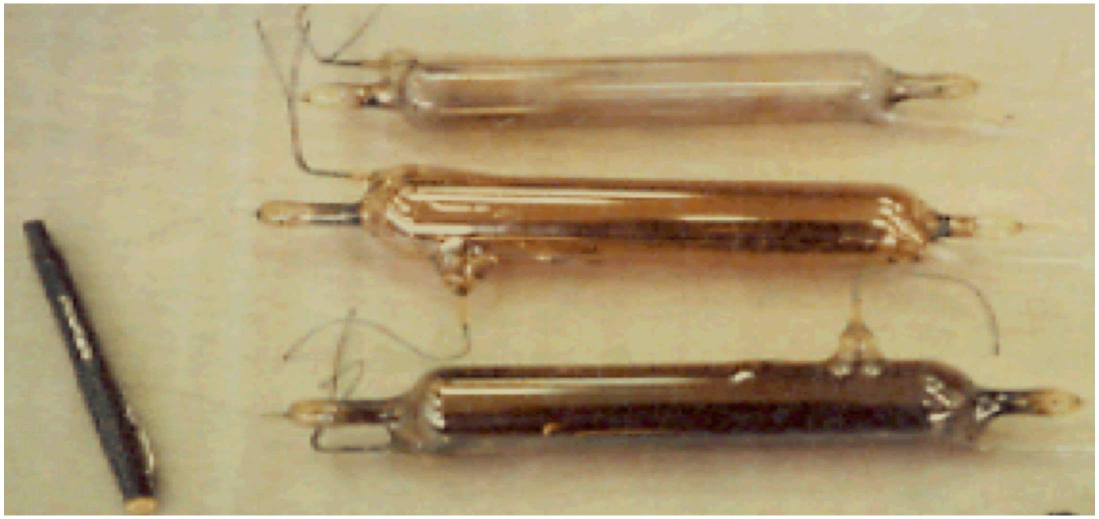
40 cm long x 10 cm diameter

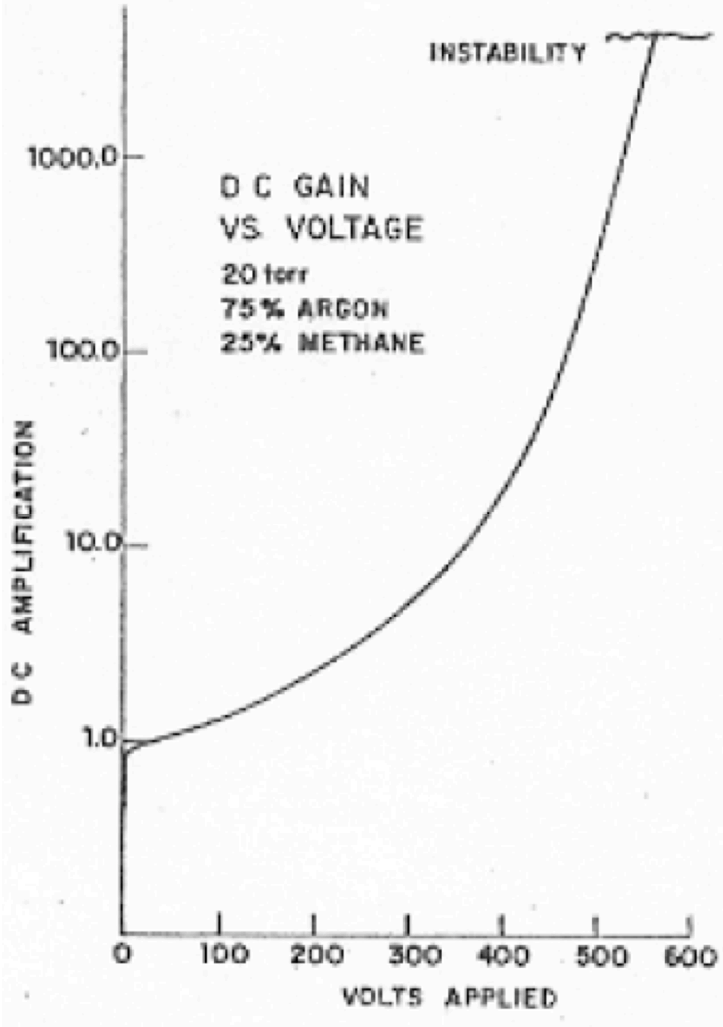
Gain = 4-5 Photons/Photon captured on WLS

Phase Space Compression ~ 2,000

Cylindrical Gas-Gain Tubes

90:10 Ar:CH4





Advantages of an Optical Amplifier/Compressor:

a) low power base HV divider string
(base only for focusing electrodes if necessary);

b) no cable driving amplifiers

c) low power at HV (photoelectron current);

d) couple many large-area photodetectors to a multi-pixel detector;

e) Compact; large photocathode area per volume of vacuum tube;

f) simple construction - one scintillating fiber/plate & no dynodes
(low cost per unit);

g) Radially focused, proximity focused, or demagnified e-optics;
collection-with a sub-ns phosphor:good jitter characteristics;

h) small cable cross-section;

I) Few High Pressure feedthrus
(optical feedthrus even for HV via conv.
1 MW/mm2 optical power limit)

j) noise immunity on the fiber-optic output
from power ripple and external
electromagnetics;

k) very good photon gain stability and tube
-tube gain uniformity for ease of calibration;

l) excellent radiation hardness, especially w/ quartz-only fiber cables and envelopes;

m) excellent optical pulse linearity;

m) gain linear with voltage, as contrasted with a photomultiplier, for modest voltage stability requirements (ripple can be 0.5% and maintain 0.5% gain stability);

n) Operation in multi-T axial magnetic fields, in some configs.

o) Very low radiation-induced backgrounds

p) Scales to very large sizes, with good capability of pressure standoff in the cylindrical configuration.

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References on request.